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Revision 0

Key Words:
Saltstone
High Density Polyethylene (HDPE)
Retention:
Permanent

SCOPING STUDY: HIGH DENSITY POLYETHYLENE (HDPE) IN SALTSTONE SERVICE (U)

February 18, 2005

PREPARED BY:
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Aiken, SC 29808

Prepared for the U.S. Department of Energy under Contract No. DE-AC09-96SR1850

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LIST OF ACRONYMS, ABBREVIATIONS, AND UNITS

ADC	Authorized Derivative Classifier
ARP/MCU	Actinide Removal Process/Modular CSSX (Caustic Side Solvent Extraction) Unit
ASTM	American Society of Testing and Materials
CSSX	Caustic Side Solvent Extraction
DDA	Deliquification, Dissolution, and Adjustment
EDTA	ethylenediaminetetraacetate
EPA	Environmental Protection Agency
ETF	Effluent Treatment Facility
GCL	geosynthetic clay liner
GM	geomembrane
GRI	Geosynthetic Research Institute
GSE	GSE Lining Technology, Inc.
HDPE	high density polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
HP-OIT	high pressure - oxidative induction time
Inc.	incorporated
INEEL	Idaho National Engineering and Environmental Laboratory
LCS	low curie salt solution
LLC	limited Liability Company
LMDPE	linear medium density polyethylene
MMES	Martin Marietta Energy Systems, Inc.
N	no
No.	number
NRC	Nuclear Regulatory commission
OIT	oxidative induction time
PA	Performance Assessment
QA/QC	quality assurance / quality control
QF	quality factor
R	universal gas constant
SCR	stress crack resistance
SDF	Saltstone Disposal Facility
Std-OIT	standard - oxidative induction time
SWPF	Salt Waste Processing Facility
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
U	unclassified
U.S.	United States
USDHEW	United States Department of Health, Education, and Welfare
USEPA	United States Environmental Protection Agency
UV	ultraviolet
WSRC	Westinghouse Savannah River Company
Y	yes

A	constant
A_f	fractional area of holes in the HDPE geomembrane
C_o	initial pore water concentration
CN	curve number
D	diameter
D_m	molecular diffusion coefficient
D_e	effective diffusion coefficient
E_a	activation energy
J	flux
K_d	partition coefficient
K_{sat}	saturated hydraulic conductivity
L	thickness or length
N	porosity
P	initial geomembrane OIT value
R	radius
S	OIT depletion rate
t	incubation time or time to antioxidant depletion
T	test temperature
Vol	volume
β^-	Beta particle
τ	tortuosity
Ci/gal	curie per gallon
cm/s	centimeter per second
cm^2	square centimeter
cm^2/yr	square centimeter per year
ft	feet
ft^2	square feet
g/cm^3	grams per cubic centimeter
g/m^2-day	grams per square meter – day
hrs/yr	hours per year
in	inch
j/mol	joule per mole
kJ/mol	kilo joule per mole
kPa	kilopascals
K	degrees Kelvin
L	liter
m^2	square meters
mg/L	milligram per liter
mg/m^2 year	milligram per square meter - year
mil	thousandth of an inch
min	minute
mm	millimeter
mm^2	square millimeter

Mrad	million rads
mrem/hr	millirem per hour
rads/hr	rads per hour
yrs	years
°	degrees
°C	degrees Celsius
°F	degrees Fahrenheit
′	foot
#	number
%	percent

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1 EXECUTIVE SUMMARY

An evaluation of the use of High density polyethylene (HDPE) geomembranes in Saltstone service has been conducted relative to the potential HDPE degradation in Saltstone service and documented herein. Additionally, conservative estimates of the nitrate groundwater concentrations resulting from the disposal of Saltstone within a vault consisting of both concrete and a HDPE geomembrane have been made.

HDPE geomembranes in Saltstone service will degrade over time through antioxidant depletion, followed by a combination of thermal oxidation and irradiation that produces embrittlement, and leads finally to tensile stress cracking of the embrittled geomembrane. Embrittlement and cracking of the HDPE geomembrane will occur slowly over a long period of time, with the bulk of the geomembrane remaining intact and functioning as a diffusion barrier. However the HDPE geomembrane will much more quickly lose its functionality as an advection barrier unless it is immediately backed up by another hydraulic barrier such as concrete or a geosynthetic clay liner (GCL).

The use of a HDPE geomembrane in combination with concrete as the diffusion barrier greatly reduces the nitrate groundwater concentrations over that of concrete use alone. The improvement is up to five orders of magnitude better for the first few hundred years and then the improvement declines over time until at 10,000 years the combination is only slightly better than concrete alone. However the benefit of an HDPE geomembrane is to slow the release of nitrate over time, significantly reduce the peak flux of nitrate out of the vault, and significantly reduce the peak nitrate groundwater concentration.

On this basis it is concluded that a Performance Assessment (PA) can probably justify taking credit for a HDPE geomembrane as one component of a multi-component diffusion barrier. Additionally the Environment Agency of England and Wales has produced a HDPE degradation model (Needham et al. 2004), which can be utilized as the basis for estimating the degradation of HDPE geomembranes in Saltstone service in terms of geomembrane hole production over time.

The following are the primary recommendations associated with the use of HDPE geomembranes in Saltstone service:

- It is recommended that irradiation of the HDPE geomembrane be maintained below a total dose of 2.6 Mrad over 10,000 years.
- It is recommended that the HDPE geomembrane be utilized as one component of a multi-component diffusion barrier, consisting of a GCL, HDPE geomembrane, and concrete, with the HDPE geomembrane placed on the exterior of the concrete vault sandwiched directly between the concrete and GCL to the extent practicable. This arrangement allows the vault concrete to provide radiation shielding for the geomembrane, improves diffusional properties by having the concrete and geomembrane in intimate direct contact, improves the hydraulic properties by allowing the GCL to hydraulically plug any holes created by tensile stress cracking of the geomembrane, and maintains a diffusion rather than advection driven contaminant transport system by having the components back one another up.

2 INTRODUCTION

An evaluation of the use of high density polyethylene (HDPE) geomembranes in Saltstone service has been conducted due to the potential benefits that could be derived from such usage. HDPE is one of the simplest hydrocarbon polymers and one of the most common polymers utilized in the production of geomembranes, which means that its costs are relatively low. Additionally, HDPE geomembranes have an extremely low permeability and an extremely low water vapor diffusional flux, which means that it is a good barrier to contaminant transport. The primary consideration in association with HDPE geomembranes in Saltstone service is the potential impact of Saltstone on the degradation of the HDPE geomembranes. Therefore, the evaluation documented herein has primarily focused upon the potential HDPE degradation in Saltstone service.

The following potential HDPE geomembrane degradation mechanisms were evaluated for HDPE geomembranes in Saltstone service:

- Ultraviolet (UV) radiation
- Chemical
- Antioxidant Depletion
- Thermal Oxidation
- High Energy Irradiation
- Tensile Stress Cracking
- Biological

In addition, conservative estimates of the nitrate groundwater concentrations resulting from the disposal of Saltstone within a vault consisting of a minimum eight inches of concrete and a 100-mil HDPE geomembrane have been made.

3 SALTSTONE CHARACTERISTICS

3.1 Saltstone Overview

Saltstone is a dense, micro-porous, monolithic, low-level radioactive waste form produced by mixing low-level radioactive salt solution (~47% by weight) with blast furnace slag (~25% by weight), flyash (~25% by weight), and cement or lime (~3% by weight) to form a grout, which is pumped into vaults and subsequently solidifies (MMES 1992).

The low-level radioactive salt solutions received at the Saltstone Processing Facility (SPF) will originate from the following processes (personal communications with Maria Rios-Armstrong 2004):

- Effluent Treatment Facility (ETF),
- Deliquification, Dissolution, and Adjustment (DDA) process (the salt solution produced from this process is called Low Curie Salt (LCS) solution),
- Actinide Removal Process/Modular CSSX (Caustic Side Solvent Extraction) Unit (ARP/MCU) process (anticipated to come on-line in fiscal year 2007), and
- Salt Waste Processing Facility (SWPF) process (anticipated to come on-line in fiscal year 2009).

These salt solutions are expected to contain 15-32% (by weight) soluble salts, with an expected average of about 28% (by weight). The specific gravity of the solution is expected to range from 1.1 to 1.28, with an expected average of about 1.25 (MMES 1992).

3.2 Saltstone Physical Characteristics

Saltstone has a porosity of approximately 0.42 (WSRC 1993), an effective diffusion coefficient (D_m/τ) of approximately 0.16 cm^2/yr (MMES 1992), and an initial saturated hydraulic conductivity of approximately 1.0E-11 cm/s (WSRC 1993; Cook 2004). It is assumed that the saturated hydraulic conductivity will increase over time to 1.0E-09 cm/s after 10,000 years (Cook 2004). After burial, it is anticipated that the Saltstone will remain essentially saturated due to it high capillary suction (Cook 2004). The specific gravity of Saltstone is expected to range from 1.6 to 1.8, with an expected average of about 1.7 (MMES 1992).

3.3 Saltstone Chemical Characteristics

The solid components of Saltstone (i.e. blast furnace slag, flyash, and cement or lime), which make up 53% of the Saltstone by weight, consist primarily of the following in descending order: silicon dioxide, aluminum oxide, calcium oxide, magnesium oxide, and iron (III) oxide. The blast furnace slag also contains sulfides, which produces reducing conditions within the Saltstone. The primary soluble salts present within the salt solution, which makes up 47% of the Saltstone by weight, include in descending order: sodium nitrate, sodium hydroxide, sodium nitrite, sodium aluminum hydroxide ($NaAl(OH)_4$), sodium carbonate, and sodium sulfate. Saltstone results from the mixture of the solid components with the salt solution and the subsequent hydration and other chemical reactions between the two. Saltstone is best described as an alkaline, reducing, micro-porous, cementitious matrix, consisting of solids such as calcium aluminosilicate and containing a solution of salts within its pore structure (Saltstone pore fluid). The pore fluid consists predominately of sodium, nitrate, and nitrite. (MMES 1992) It has been estimated that the pore fluid contains 74,234 mg/L nitrate/nitrite (WSRC 2002). The Saltstone also contains many metals most of which are contained within the cementitious matrix or are insoluble under the alkaline, reducing conditions. Finally, the salt solution may contain relatively low concentrations of organics such as benzene, butanol, isobutanol, isopropanol, methanol, phenoltetraphenylborate, toluene, tributylphosphate, and EDTA (Chandler 2004). Since many of these organics are volatile, it is highly likely that the Saltstone itself will contain significantly less organics than the salt solution due to the elevated temperatures resulting from the heat of hydration and radioactive decay (see section 3.4 below).

3.4 Saltstone Temperature

Although Vault #2 will have a cylindrical configuration (see Section 5.1), Shadday (2004) utilized an existing trapezoidal vault model to estimate the temperature over time from Saltstone produced from salt solution containing 0.2 curies/gallon of cesium-137 (Cs-137). Elevated temperatures result from both heat of hydration and radioactive decay. The temperature within the Saltstone mass is maintained below 95°C since the grout product quality degrades above this temperature (Hayes 2005a). The temperature over time was estimated at the following two locations:

- Center base of the vault immediately adjacent to the Saltstone
- Center base of the vault 1-foot below the Saltstone through 1-foot of concrete

Figure 1 provides a schematic of the vault configuration modeled. Figure 2 provides the average yearly temperatures for each of these locations over a 199-year period. As can be seen there is very little difference in temperatures between these locations. The average yearly temperature over the first year is 64.36 °C and 61.88 °C, respectively, adjacent to the Saltstone and 1-foot below the Saltstone. After year 199 this declines to an average yearly temperature of 28.45 °C and 28.41 °C, respectively, adjacent to the Saltstone and 1-foot below the Saltstone. Appendix A provides the average yearly temperature data for each of these locations (i.e. adjacent to the Saltstone and 1-foot below the Saltstone) over a 199-year period.

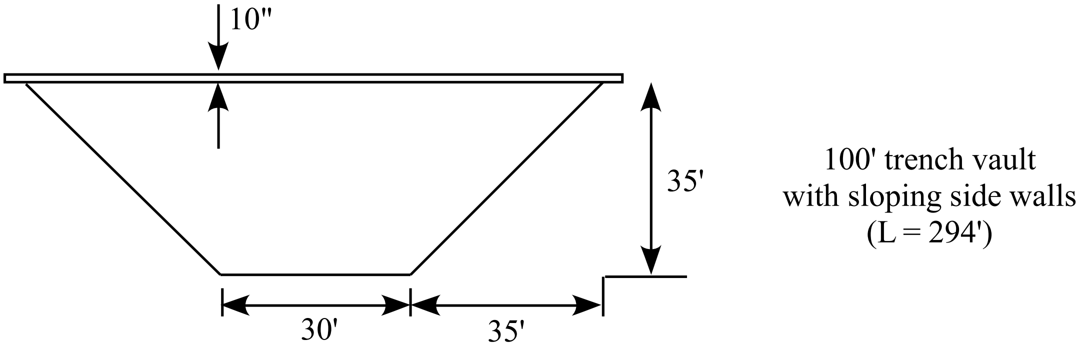


Figure 1. Trapezoidal Vault Configuration

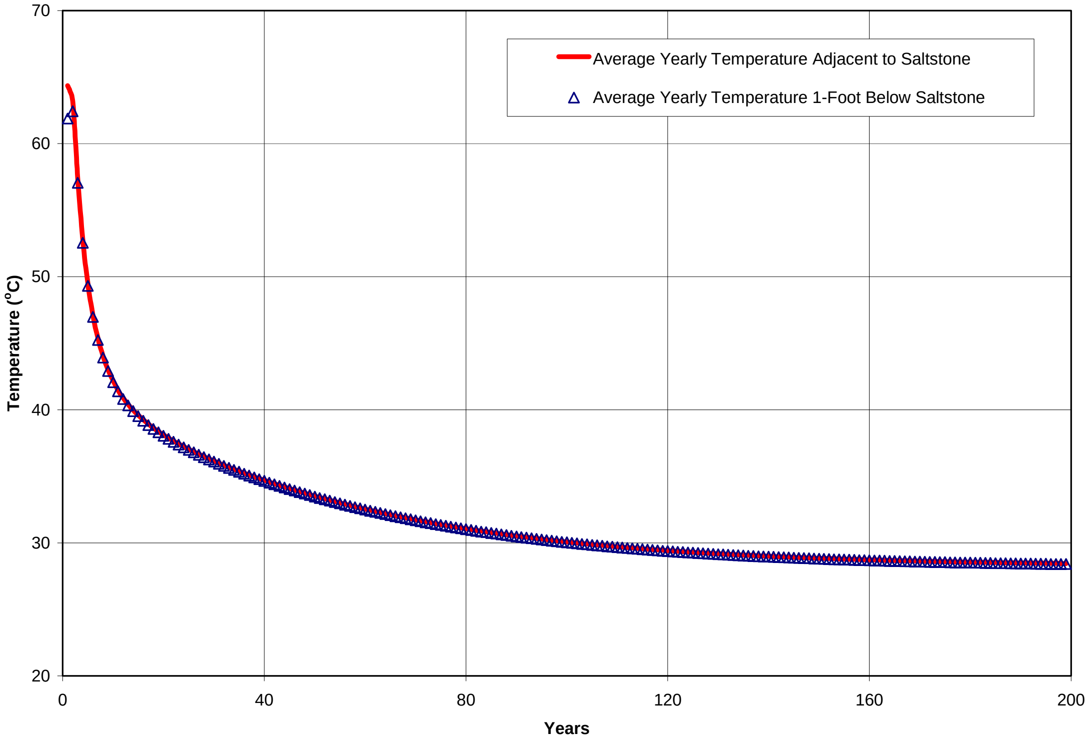


Figure 2. Average Yearly and Cumulative Average Temperatures over a 199-year Period

3.5 Saltstone Radioactivity

The LCS produced from the DDA process (see Section 3.1) is assumed to contain 0.2 curies/gallon of cesium-137 with a total curie content of 0.52 curies/gallon (Hayes 2005a). The salt solutions produced from the later ARP/MCU and SWPF processes will have significantly lower curie contents than the LCS. Vault #2 will receive Saltstone produced from LCS, whereas future vaults will receive Saltstone produced from the lower curie content salt solutions. Therefore, this study will focus upon Saltstone produced from LCS.

The primary contributor to the dose rate associated with Saltstone made from LCS is the Cs-137. Cs-137 has a half-life of 30.07 years, decays by β^- decay, and emits predominately gamma rays and beta particles (i.e. electrons) (USDHEW 1968; Tuli 2000). Within Calculation Number N-CLC-Z-00009 (Barnett 2003) the dose rate in mrem/hr at time zero through 0 to 22 inch thick concrete was calculated for Saltstone made from 0.378 Ci/gal Cs-137 salt solution. Within Calculation Number N-CLC-Z-00005 (Willison 2003) it was determined that the dose rate associated with Saltstone could be directly scaled to the curie loading of Cs-137. Figure 3 and Table 1 provide the dose rate at time zero through 0 to 22 inch thick concrete for Saltstone made from 0.378 Ci/gal Cs-137 salt solution (N-CLC-Z-00009). Additionally Table 1 provides the dose rate from Saltstone made from 0.2 Ci/gal Cs-137 salt solution based upon directly scaling to the curie loading of Cs-137 (N-CLC-Z-00005). Figure 3 also provides the exponential best fit equation for the dose rate through concrete for each of these Cs-137 levels.

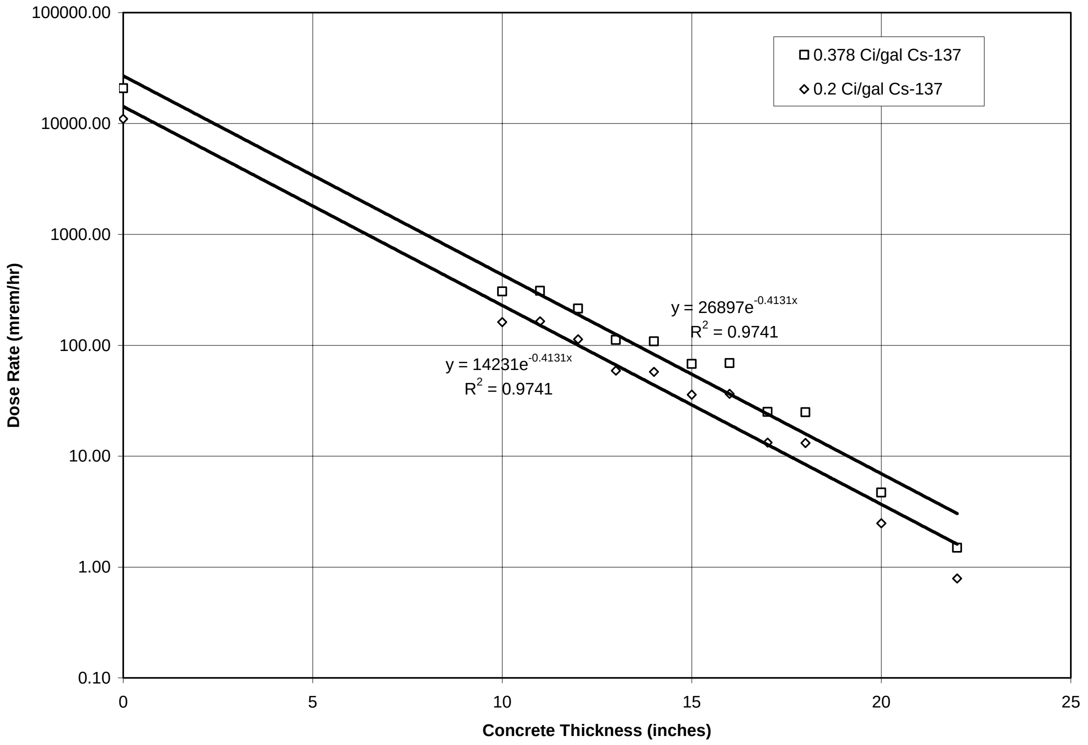


Figure 3. Saltstone Dose Rate (mrem/hr) through Concrete Shielding at Time Zero

Table 1. Saltstone Dose Rate (mrem/hr) through Concrete Shielding at Time Zero

Concrete Thickness (inches)	Dose Rate from 0.378 Ci/gal Cs-137 Saltstone (mrem/hr)	Dose Rate from 0.2 Ci/gal Cs-137 Saltstone [1] (mrem/hr)
0	20795.54	11002.93
10	305.71	161.75
11	310.18	164.12
12	214.01	113.23
13	111.55	59.02
14	108.61	57.46
15	67.70	35.82
16	68.87	36.44
17	25.07	13.26
18	24.88	13.16
20	4.70	2.49
22	1.49	0.79

[1] Dose Rate from 0.2 Ci/gal Cs-137 Saltstone = (0.2 / 0.378) × (Dose Rate from 0.378 Ci/gal Cs-137 Saltstone)

The conversion between rem and rad is as follows (Salvato1972):

Rads = Rems/QF

The quality factor (QF) for x-rays, gamma rays, electrons, and positrons is one (Salvato 1972); therefore for predominately Cs-137 decay, as is the case for LCS Saltstone, the quality factor is one making a rad equivalent to a rem (i.e. Rad = Rem). Based upon this conversion and the exponential best fit equation from Figure 3, the Saltstone dose rate through concrete at time zero has been determined in rads for 0.2 Ci/gal Cs-137 Saltstone (Table 2)

Table 2. Saltstone Dose Rate in Rads/hr through Concrete Shielding at Time Zero

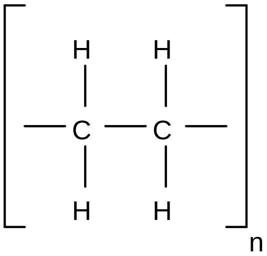
Concrete Thickness (inches)	0.2 Ci/gal Cs-137 Saltstone (Rads/hr)
0	1.10E+01
2 [1]	6.23E+00
4 [1]	2.73E+00
6 [1]	1.19E+00
8 [1]	5.22E-01
10	1.62E-01
12	1.13E-01
14	5.75E-02
16	3.64E-02
18	1.32E-02
20	2.49E-03
22	7.90E-04

[1] Dose rates for 2, 4, 6, and 8 inches were calculated based upon the exponential best fit equations from Figure 3 (i.e. $y = \frac{14{,}231e^{-0.4131x}}{1000}$).

4 HIGH DENSITY POLYETHYLENE (HDPE) CHARACTERISTICS

4.1 General HDPE Overview

Polyethylene is the simplest hydrocarbon polymer, produced from the polymerization of resins consisting of a dominant ethylene monomer, which has unsaturated bonds, and α-olefin copolymers such as butane, hexane, methyl pentane or octane. The repeating unit of polyethylene has the structural form shown below:



Polymerization results in a long 'zigzag' chain structure of this repeating unit with side branching due to the copolymers. Polyethylene is semicrystalline, containing both amorphous (0.853 g/cm^3) and crystalline regions (1.004 g/cm^3). The copolymers, which produce the side branching, result in a lower density and lower crystallinity. Polyethylene is considered a thermoplastic, since it can be repeatedly heated and shaped as desired and will maintain the remolded shape when cooled. (Koerner 1998; Needham et al. 2004)

High density polyethylene (HDPE) is one of the most common polymers utilized in the production of geomembranes (Koerner 1998). HDPE geomembranes consist of 95-98% resin, 2-3% carbon black, and 0.25-1% antioxidants. The crystallinity of HDPE geomembranes ranges between 44 to 67.5%, and they have a minimum sheet density of 0.940 g/cm^3. (GRI 2003; Koerner and Hsuan 2003; Needham et al. 2004) It has an extremely low permeability (2.0E-13 cm/s) (USEPA 1994a; USEPA 1994b) and an extremely low water vapor diffusional flux (~0.006 g/m^2-day) (Rumer and Mitchell 1995). Rumer and Mitchell (1995) report that "diffusion of water or solvent through HDPE geomembranes can only occur in a vapor state". Rowe et al. (1995) and Rowe (2004) report that "HDPE geomembranes act as an excellent diffusion barrier to water and hydrated ions such as chloride with negligible migrations being observed in tests that have been running for over a decade." Rowe and Sangam (2002) reporting on the work of August et al. (1992) state that metals can not readily diffuse through HDPE geomembranes. Therefore it is generally assumed that no significant diffusion of non-volatile, dissolved ions occurs through intact HDPE.

4.2 HDPE Geomembrane Degradation Mechanisms

HDPE geomembranes can degrade over time through the following mechanisms, which are discussed in detail in the succeeding sections (Koerner 1998; Needham et al. 2004; Rowe 2004):

- Ultraviolet (UV) radiation
- Chemical
- Antioxidant Depletion
- Thermal Oxidation
- High Energy Irradiation

- Tensile Stress Cracking
- Biological

4.2.1 Ultraviolet (UV) Degradation

HDPE geomembrane degradation due to short-wavelength ultraviolet (UV) radiation (i.e. sunlight) exposure has been extensively studied both in the laboratory and field (Koerner 1998; Koerner and Hsuan 2003). Exposure to UV radiation and subsequent penetration of UV radiation into the polymer structure causes polymer degradation by chain scission and bond breaking. Additionally, photo-oxidation due to UV radiation and atmospheric exposure causes significantly faster antioxidant depletion than thermal oxidation (Needham et al. 2004). However current HDPE geomembrane formulations typically contain 2 to 3% carbon black and may contain other ultraviolet chemical stabilizers to minimize ultraviolet degradation. Due to carbon black usage, UV radiation is not considered a significant degradation mechanism for short-term exposures associated with construction, where the geomembrane is covered in a timely manner. Typically exposures of less than several years is not considered a concern, since manufacturers' warranties for up to 20 years are available for exposed geomembranes. (Koerner 1998; Needham et al. 2004)

4.2.2 Chemical Degradation

A significant number of studies have been conducted in the laboratory on leachate effects on HDPE geomembranes and in general no significant deterioration in physical or mechanical properties has been recorded in any of them (Needham et al. 2004). Based upon these tests, HDPE manufacturers' have compiled chemical resistance charts which are generally reliable (Koerner 1998). Additionally these tests have generally shown that municipal solid waste landfill leachate is relatively benign towards HDPE geomembranes, therefore chemical resistance tests are now rarely required in the United States (Needham et al. 2004). However the following chemical degradation mechanisms have been reported:

- HDPE geomembrane contact with some organic compounds, either as a concentrated solution or as pure liquids, can cause absorption of the organic in to HDPE which causing subsequent swelling and softening of the geomembrane. In general this condition is reversed and the geomembrane returns to its original condition once the organic is no longer present at the geomembrane surface. (Needham et al. 2004)
- The oxidation rate of HDPE geomembranes in contact with solutions containing transition metals such as copper, manganese, and iron may be significantly increased at the surface of the geomembrane, since the dissolved metals may break down hydroperoxides in the geomembrane and create additional free radicals. (Rowe and Sangam 2002; Needham et al. 2004).
- HDPE geomembranes are generally not compatible with strong oxidizers such as ozone (GSE 2004).

The following are the conclusions of several chemical resistance tests that have been performed on HDPE geomembranes in low-level radioactive waste disposal service in contact with solutions similar to that of Saltstone pore water (i.e. high pH salt solutions):

- Whyatt and Fansworth (1990) evaluated a 60-mil HDPE geomembrane in simulated short-term (up to 120 days) chemical compatible tests with a high pH (~14) inorganic solution at 90°C and subjected them to radiation doses ranging from 0.6 to 38.9 Mrad. The solution consisted predominately of the following in descending order: sodium, nitrite, nitrate, aluminum, potassium, and sulfate. It was concluded that the HDPE geomembrane was chemically compatible with the inorganic solution. With immersion in the solution but no radiation dose, no significant sample dimensional changes occurred, and the yield, break, and puncture strengths and their associated elongations all increased (i.e. properties improved) over time. However with immersion in the solution and an applied radiation dose, the break strength and elongation decreased (i.e. properties degraded), while yield and puncture strengths and their associated elongations all increased (i.e. properties improved). The 38.9 Mrad dose was slightly greater than the break elongation half-dose value (see Section 4.2.5 for the definition of the half-dose value) of the HDPE geomembrane under the conditions tested. No other properties tested were near the half-dose value. From this work it was also concluded "that radiation does not make the liner more susceptible to chemical degradation."
- Compatibility testing was performed on the 60-mil smooth HDPE geomembrane planned for the Hanford Grout facility. HDPE samples were exposed to a dose rate of 740,000 rads per hour until a total radiation dose of 16 Mrad or 37 Mrad was reached. The total dose of 37 Mrad resulted in a greater than 25% decrease in geomembrane strength and elasticity. Then the HDPE was immersed in a 194°F solution with a pH of 9.2 and a concentration of inorganics of 368,336 mg/L. It was stated that under these conditions the HDPE showed no unacceptable effects. (INEEL 2004)

4.2.3 Antioxidant Depletion

Antioxidants are added to HDPE geomembranes primarily to prevent thermal oxidative degradation (see Section 4.2.4). As long as significant antioxidants are present within a HDPE geomembrane, as measured by Oxidative Induction Time (OIT) tests, thermal oxidative degradation will be prevented and the mechanical properties of the geomembrane will remain essentially unchanged. However after the antioxidants have been depleted, thermal oxidation of the geomembrane can begin. Typical antioxidants packages consist of a phosphite and a hindered phenol at 0.1 to 1.0 weight percent of the geomembrane. Phosphites are most effective at higher temperatures and are used as manufacturing process stabilizers, whereas Hindered phenols are effective over a wide temperature range and are used as long-term field stabilizers. (Koerner 1998; Hsuan and Koerner 1998; Sangam and Rowe 2002; Mueller and Jakob 2003; Rowe 2004; Needham 2004)

The OIT time determined from OIT tests is related to the quantity and type of antioxidants in the polymer. OIT tests use a differential scanning calorimeter with a special testing cell capable of sustaining pressure. In the standard OIT test (ASTM D3895) a 5 mg specimen is brought to a temperature of 200°C and a pressure of 35 kPa under a nitrogen atmosphere. Oxygen is then introduced and the test is terminated when an exothermal peak is reached. The OIT time is the time from oxygen introduction to the exothermal peak. The high pressure OIT (HP-OIT) test (ASTM D5885) is conducted similar to the standard test except it is conducted at a temperature of 150°C and a pressure of 3,500 kPa are utilized.

Three major antioxidant depletion studies have been performed: Hsuan and Koerner 1998; Sangam and Rowe 2002; and Mueller and Jakob 2003. Each of these studies is discussed in the succeeding sections.

4.2.3.1 Hsuan and Koerner (1998) Antioxidant Depletion Study

Hsuan and Koerner (1998) reported on twenty-four months of HDPE geomembrane antioxidant depletion testing. The HDPE geomembrane tested was taken from a single roll of commercially available 60 mil thick HDPE. The primary antioxidants in this geomembrane were probably phosphites and hindered phenols (Hsuan and Guan 1997). OIT tests, which provide a relative measure of the total antioxidants within the geomembrane, were initially performed. The following were the initial OIT measurements for this geomembrane:

- Standard-OIT = 80.5 min (The Std-OIT value for pure unstabilized (no antioxidants) HDPE resin was found to be 0.5 min)
- High Pressure-OIT = 210 min (The HP-OIT value for pure unstabilized (no antioxidants) HDPE resin was found to be 20 min)

Four sets of five columns for a total of twenty were maintained at elevated temperatures of 85, 75, 65, and 55°C and under a static normal load of 260 kPa and a 300 mm head of tap water. The top surface of the HDPE was saturated sand and the bottom surface was dry sand vented to the atmosphere. Samples were retrieved at various time intervals over a two year period and analyzed for numerous physical, mechanical, and chemical properties including OIT.

Although the OIT value decreased with time, the testing was not conducted to antioxidant depletion. Therefore no significant changes in physical and mechanical properties (i.e. density, melt flow index, yield stress, yield strain, break stress, and break strain) were noted over the 24 month period, since these properties remain unchanged as long as antioxidants exist in the geomembrane (i.e. OIT values greater than that of unstabilized HDPE resin).

Hsuan and Koerner (1998) plotted both the standard and high pressure OIT data for each of the four test temperatures as the natural logarithm of OIT versus incubation time. This produced a linear response for each test temperature for each OIT methodology, where the OIT depletion rate for each temperature is the slope of its respective line and the y-intercept is the natural logarithm of the initial geomembrane OIT value. The equation for the line then becomes:

$\ln(OIT) = \ln(P) - St$, where OIT = OIT (minutes); S = OIT depletion rate (minutes/month); t = incubation time (months); and P = the initial geomembrane OIT value (i.e. a constant)

Based upon these plots Hsuan and Koerner (1998) determined the antioxidant depletion rates for each OIT methodology for each test temperature as shown in Table 3.

Table 3. Hsuan and Koerner (1998) Antioxidant Depletion Rates

Temperature (°C)	S $_{\text{Std-OIT}}$ (min/month)	S $_{\text{HP-OIT}}$ (min/month)
85	0.1404	0.0661
75	0.0798	0.0387
65	0.0589	0.0284
55	0.0217	0.0097

Hsuan and Koerner (1998) then used the Arrhenius equation to extrapolate the OIT depletion rate to lower temperatures more representative of typical field condition. The Arrhenius equation can be use to expressed by:

$$S = Ae^{-E/RT}$$

$\ln(S) = \ln(A) + (-E_a / R)(1/T)$, where S = OIT depletion rate (see Table 3); E_a = activation energy of the antioxidant depletion reaction (kJ/mol); R = universal gas constant (8.31 j/mol); T = test temperature in absolute Kelvin (K); and A = constant.

A plot of ln(S) versus 1/T results in a linear plot as shown in Figure 4. The activation energy of the antioxidant depletion reaction is obtained from the slope of the line. From the Arrhenius plot Hsuan and Koerner (1998) determined the Arrhenius equation associated with each OIT test method and the associated activation energy as shown in Table 4. The Table 4 equations were utilized to determine the OIT depletion rate (S) associated with various temperatures (see Table 5). Then the time to antioxidant depletion was determined for select temperatures (see Table 5) using the following equation:

$\ln(OIT) = \ln(P) - St$, where OIT = antioxidant depleted OIT value (minutes) taken as the OIT value of pure unstabilized (no antioxidants) HDPE resin; S = OIT depletion rate (minutes/month) (see Table 5); t = time to antioxidant depletion (months); and P = the original value of OIT of the geomembrane (i.e. a constant)

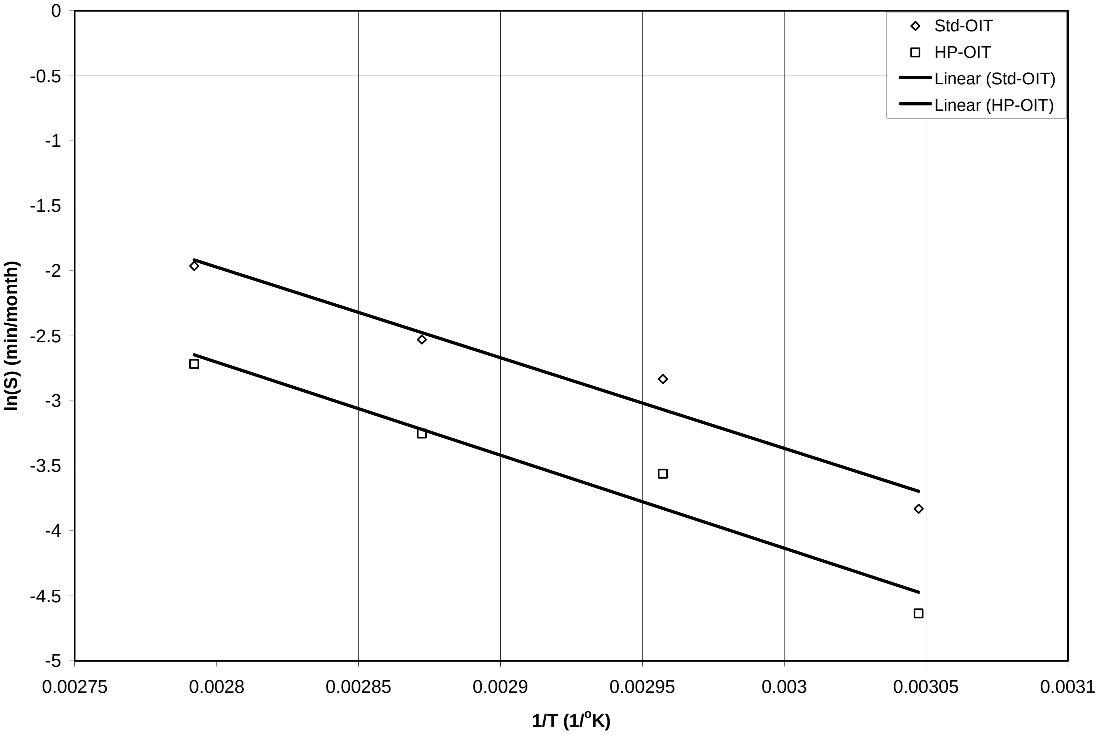


Figure 4. Hsuan and Koerner (1998) Arrhenius Plot

Table 4. Hsuan and Koerner (1998) Arrhenius Equations and Activation Energy

OIT Test Method	Arrhenius equation	E_a (kJ/mol)
Std-OIT	Ln(S) = 17.045 – 6798/T	56
HP-OIT	Ln(S) = 16.850 – 6989/T	58

Table 5. Hsuan and Koerner (1998) OIT depletion Rate (S) and Time to Antioxidant Depletion

Temperature (°C)	$S_{\text{std-OIT}}$ (minute/month)	$t_{\text{std-OIT}}$ (yrs)	$S_{\text{HP-OIT}}$ (minute/month)	$t_{\text{HP-OIT}}$ (yrs)
13	0.0012	348.1	0.0005	381.6
15	0.0014	295.2	0.0006	322.1
20	0.0021	197.4	0.0009	213.0
25	0.0032	133.8	0.0014	142.8
33	0.0057	73.7	0.0025	77.4
40	0.0094	44.9	0.0042	46.5

Based upon their 24 months of testing, Hsuan and Koerner (1998) postulated that HDPE degradation due to thermal oxidation occurs in the following three stages:

- Stage A: Antioxidant depletion period,
- Stage B: Induction period, and
- Stage C: Polymer thermal oxidation period.

After 24 months of testing, the HDPE degradation was still in the antioxidant depletion period, based upon this data Hsuan and Koerner (1998) estimated that the antioxidant depletion period would last approximately 200 years at a temperature of 20 °C. Koerner (1998) has additionally estimated that the induction period (i.e. the time between antioxidant depletion and onset of thermal oxidation) would last from 20 to 30 years based upon the examination of exhumed HDPE milk containers at the bottom of a landfill. Thus in a buried environment at 20 °C, they estimate a time span of approximately 220 years with essentially no degradation of physical and mechanical properties.

4.2.3.2 Sangam and Rowe (2002) Antioxidant Depletion Study

Sangam and Rowe (2002) reported on approximately thirty-three months of HDPE geomembrane antioxidant depletion testing. The HDPE geomembrane tested was a GSE Lining Technology, Inc. 80-mil thick smooth HDPE manufactured from a copolymer resin with a density of 0.940 g/cm^3, a carbon black content of 2.54%, and an initial standard OIT of 133 minutes. It was assumed that the primary antioxidants in this geomembrane were phosphites and hindered phenols based upon the previous work of Hsuan and Guan (1997).

HDPE coupons were immersed in air, tap water, and synthetic landfill leachate (i.e. exposed on both sides), each at temperatures of 22 ± 2, 40, 55, 70, and 85°C. Samples were retrieved at various time intervals over a thirty-three month period and analyzed for primarily standard OIT. The synthetic landfill leachate consisted of approximately 15,000 mg/L inorganic ions, 7,500 mg/L volatile fatty acids, 5000 mg/L of a surfactant, and less than 10 mg/L trace heavy metals.

Sangam and Rowe (2002) plotted the standard OIT data for each of the immersion medium (i.e. air, tap water, and synthetic landfill leachate) at each of the five test temperatures as the natural logarithm of OIT versus incubation time. This produced a straight line for each test exposure condition (i.e. immersion medium and temperature) suggesting that the antioxidant depletion follows first-order decay, with the OIT depletion rate represented by the slope of the line. At any time (t), the OIT value which represents the remaining amount of antioxidants the geomembrane can be expressed as:

$OIT(t) = OIT_0\, e^{-St}$, where OIT(t) = OIT at any time, t, in minutes; OIT_0 = initial OIT in minutes; S = rate of antioxidant depletion in month^{-1}.; t = time in months

This resulted in the inferred depletion rates provided in Table 6.

Table 6. Sangam and Rowe (2002) Inferred Depletion Rates (S = month^{-1})

Temperature (°C)	Air	Water	Leachate
85	0.1094	0.1746	0.4074
70	0.0497	0.1050	-
55	0.0226	0.0470	0.1504
40	0.0152	0.0362	0.0886
22	0.0023	0.0043	0.0188

The Table 6 depletion rates determined at elevated temperatures can be extrapolated to typical field temperatures using the Arrhenius equation (a time-temperature superposition principal) in order to estimate the field service life.

$$S = A\,e^{-E_a/RT}$$

$\ln(S) = \ln(A) + (-E_a / R)(1/T)$, S = OIT depletion rate (see Table 6); E_a = activation energy in J/mol; R = 8.314 J/mol K (universal gas constant); T = absolute temperature in K; A = constant (collisional factor)

A plot of ln(S) versus 1/T results in a linear plot as shown in Figure 5. The activation energy of the antioxidant depletion reaction is obtained from the slope of the line. From the Arrhenius plot Sangam and Rowe (2002) determined the Arrhenius equation associated with each immersion medium (i.e. air, water, and leachate) and the associated activation energy. However Sangam and Rowe (2002) appear to have made a mistake in their calculations. Rather than using the temperature 40^{o}C in their calculations they appeared to have used 50^{o}C. Making this correction the derived Arrhenius equation and the inferred activation energy (E_a) for each immersion medium are summarized in Table 7. The Table 7 equations were utilized to determine the OIT depletion rate (S) associated with various temperatures (see Table 8). Then the time to antioxidant depletion was determined for select temperatures (see Table 8) using the following equation and assuming the OIT of an unstabilized HDPE to be 0.5 minute:

$\ln(OIT_D) = \ln(OIT_o) - St$, where OIT_D = antioxidant depleted OIT value of 0.5 minutes; S = OIT depletion rate (minutes/month) (see Table 5); t = time to antioxidant depletion (months); and P = the original value of OIT of the geomembrane (i.e. a constant)

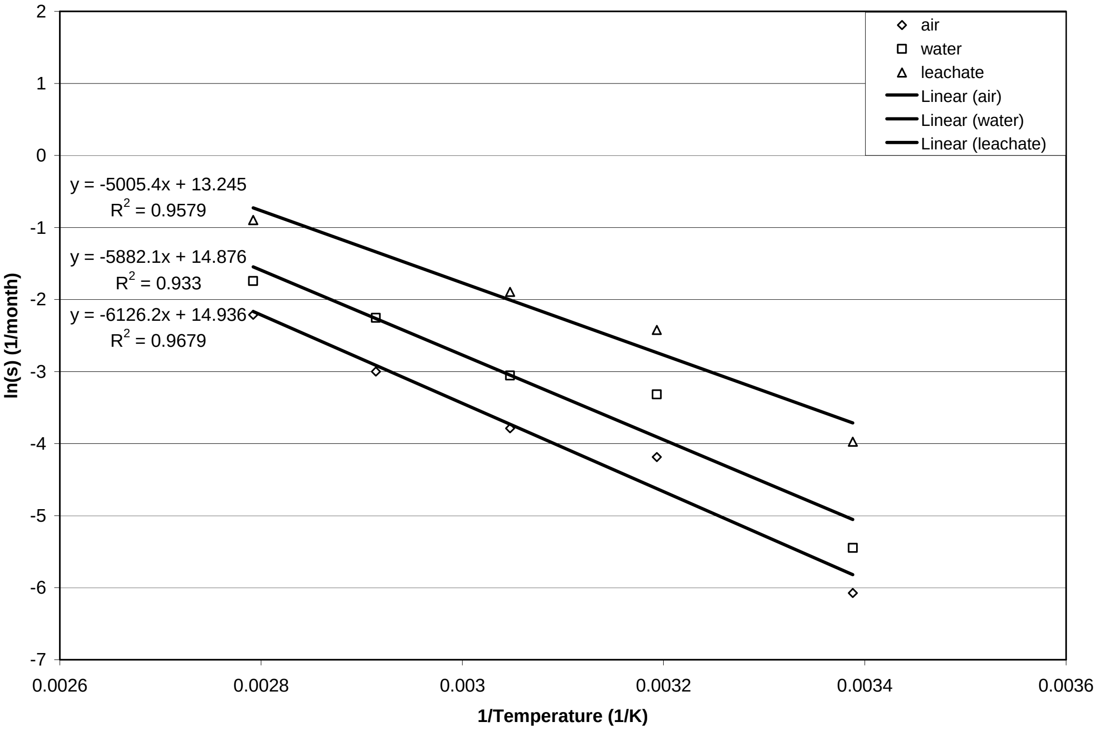


Figure 5. Sangam and Rowe (2002) Arrhenius Plot

Table 7. Sangam and Rowe (2002) Arrhenius Equations and Activation Energy

Exposure Medium	Arrhenius equation (S = month^{-1}; T = month)	E_a (kJ/mol)	R^2
Air	Ln(s) = 14.936 – 6126.2/T	50.93	0.9679
Water	Ln(s) = 14.876 – 5882.1/T	48.90	0.933
Leachate	Ln(s) = 13.245 – 5005.4/T	41.61	0.9579

Table 8. Sangam and Rowe (2002) OIT Depletion Rate (S) and Time to Antioxidant Depletion

Temp. (^{o}C)	S (month^{-1})	Air (yrs)	S (month^{-1})	Water (yrs)	S (month^{-1})	Leachate (yrs)
13	0.0015	301.3	0.0034	136.3	0.0143	32.5
15	0.0018	259.7	0.0039	118.2	0.0162	28.8
20	0.0026	180.7	0.0056	83.4	0.0217	21.4
25	0.0037	127.3	0.0078	59.6	0.0289	16.1
33	0.0063	74.4	0.0131	35.6	0.0448	10.4
40	0.0098	47.6	0.0201	23.2	0.0646	7.2

As seen in Table 8, antioxidant depletion for the range of temperatures 13 to 33 ^{o}C is estimated to be approximately twice as fast in tap water than in air and four times faster in high organic content leachate than in tap water. Sangam and Rowe (2002) state that the following regarding these estimates of antioxidant depletion:

- The Table 8 time to antioxidant depletion estimates represent a lower bound to the time and the time in the field would be expected to be longer under these exposure conditions.
- The Table 8 time to antioxidant depletion estimates are based upon having the immersion medium on both sides of the geomembrane and must be adjusted for actual field conditions (i.e. leachate is not typically located on both sides of the membrane).

4.2.3.3 Mueller and Jakob (2003) Antioxidant Depletion Study

Mueller and Jakob (2003) report on 13.6 years of HDPE geomembrane antioxidant depletion testing for immersion in air and 6 years for immersion in de-ionized water. The HDPE geomembranes tested by Mueller and Jakob (2003) consisted of nine commercially available HDPE geomembranes made by five different manufacturers from seven different resins. The geomembranes were 100-mil thick, had densities ranging from 0.940 to 0.950 g/cm^3, contained 2 to 2.5 weight percent carbon black and a few thousand ppm phenolic and phosphite antioxidants, and had an initial OIT (Al-pan at 200^{o}C) from 11 to 138 min.

HDPE samples were immersed in air and de-ionized water (i.e. exposed on both sides) at 80^{o}C. The samples immersed in air were in an oven with substantially less than 10 air changes per hour. The samples were immersed in water in glass flasks, which were opened and shook every four weeks. The water was completely changed every three months. At various times samples were removed and tested for OIT and tensile strength and elongation.

During accelerated aging in heated air, the OIT slowly decreased in a steady, exponential-like, fashion. After 13.6 years of accelerated aging in heated air, no significant changes in mechanical properties due to oxidation were detected. For aging in heated air it was found that “the relative OIT values (i.e. OIT/OIT$_{\text{intial}}$) showed roughly a common decline as a function of aging time, independent of the resin or the OIT testing temperature”.

During accelerated aging in heated water, the OIT decreased rapidly at first and then leveled off. Mueller and Jakob (2003) looked at this as a two step exponential decline with a short-term high antioxidant depletion rate and a long-term low antioxidant depletion rate. After 6 years of accelerated aging in heated water, it was found that most samples approached very low OIT values after 200 days (i.e. the antioxidant depletion rate was initially fairly high), that the antioxidant depletion rate decreased significantly after 200 days, and that oxidation of the polymer itself started after 5 years, and that deterioration proceeded quite rapidly after oxidation began at the elevated test temperature (80^{o}C). Since the phosphite stabilizer substantially determines the initial OIT and since it constitutes the bulk of the stabilizer in the HDPE geomembranes, Mueller and Jakob (2003) assume that depletion especially of the phosphite component is seen in the initial rapid OIT decrease. “The long-term antioxidant depletion time would then be determined by the migration of the remaining phenolic stabilizer. Therefore, a high initial OIT does not necessarily correlate with good long-term oxidation stability.”

Short-term antioxidant depletion rates were estimated at 0.15 to 0.3 minute/month (approximately 0.2) in water at 80^{o}C (100-200 days) and long-term antioxidant depletion rates at 0.015 to 0.03 minute/month (1000-2000 days). Most of the data appeared to be in the 0.15 minute/month (200 days) range for the short-term antioxidant depletion rate and 0.015 minute/month (2000 days) for long-term antioxidant depletion rate.

Mueller and Jakob (2003) could not estimate the antioxidant depletion time (i.e. time it takes to deplete the antioxidants and begin oxidation) at typical field temperatures using the Arrhenius equation, since they did not perform their testing at multiple temperature as required for use of the Arrhenius equation. Therefore they utilized the van't Hoff rule for the temperature dependence of antioxidant depletion time, their measured antioxidant depletion time of 5 years for HDPE GMs immersed in 80°C de-ionized water, and assumed activation energies from other studies.

$t_1(T) = t_1(T')\, e^{\frac{E_a}{R}\left[\frac{1}{T}-\frac{1}{T'}\right]}$, where $t_1(T)$ = antioxidant depletion period in years at the ambient temperature of the HDPE; $t_1(T')$ = antioxidant depletion period in years at test temperature of 80°C (i.e. 5 years); E_a = depletion process activation energy; R = universal gas constant (8.319 J/mol K); T = ambient temperature of the HDPE in K (K = 273.15 + °C); T' = test temperature in K = 273.15 + 80°C = 353.15

Table 9 provides various antioxidant depletion process activation energies that have been determined by others. These activation energies have been utilized with the van't Hoff rule to calculate estimated antioxidant depletion times per Mueller and Jakob's (2003) methodology (see Table 10). As seen in Table 10 the estimated antioxidant depletion time varies widely with the assumed activation energy. At a temperature of 33 °C the antioxidant depletion time varies from 45 to 930 years with the utilization of activation energies of 42 and 100 kJ/mol, respectively. Mueller and Jakob (2003) believe that an activation energy of 60 kJ/mol is a very low activation energy which is expected to represent the lower limit of antioxidant depletion time. At a temperature of 33 °C and an activation energy of 60 kJ/mol the antioxidant depletion time would be approximately 103.6 years.

Table 9. Antioxidant Depletion Process Activation Energies

Source	Media	E_a (kJ/mol)	Comment
Hsuan-Koerner (1998)	Sand-water-air	56	Using Std-OIT test; didn't take test out to antioxidant depletion
		58	Using HP-OIT test; didn't take test out to antioxidant depletion
Sangam-Rowe (2002)	Air	51	Using Std-OIT test; didn't take test out to antioxidant depletion
	Water	49	
	Synthetic Leachate	42	
Smith et al. (1992)	Water	100	-

Table 10. Estimated Antioxidant Depletion Times

Temperature (^oC)	E_a = 42 kJ/mol Antioxidant Depletion Time (years)	E_a = 49 kJ/mol Antioxidant Depletion Time (years)	E_a = 51 kJ/mol Antioxidant Depletion Time (years)
13	142.1	248.3	291.2
15	125.8	215.2	251.0
20	93.3	151.9	174.6
25	69.9	108.4	123.0
33	44.9	64.7	71.8
40	31.0	42.1	45.9
Temperature (^oC)	E_a = 56 kJ/mol Antioxidant Depletion Time (years)	E_a = 58 kJ/mol Antioxidant Depletion Time (years)	E_a = 100 kJ/mol Antioxidant Depletion Time (years)
13	433.8	508.8	14,462.3
15	368.4	429.6	10,804.6
20	247.4	284.3	5,303.9
25	168.3	190.8	2,666.5
33	93.3	103.6	929.8
40	57.1	62.3	386.6

Mueller and Jakob (2003) determined that antioxidant depletion occurs due to diffusion out of the HDPE geomembrane and oxidative consumption. It was also determined that under conditions of low temperature and low oxygen levels, diffusion is the predominant antioxidant depletion mechanism as with typical field conditions. The diffusion rate is higher with immersion in water rather than in air. Oxidative consumption is the predominant mechanism, under conditions of high temperature and high oxygen levels. Additionally Mueller and Jakob (2003) determined that the mechanical properties of HDPE geomembrane are not significantly degraded as long as a significant OIT value is measurable.

4.2.3.4 Summary of Antioxidant Depletion Studies

Both Hsuan and Koerner (1998) and Mueller and Jakob (2003) determined that no significant changes in physical and mechanical properties of the HDPE geomembrane occur until the antioxidants are essentially depleted. Sangam and Rowe (2002) and Mueller and Jakob (2003) determined that the antioxidant depletion rate is dependent upon the medium within which the HDPE geomembrane is immersed. Sangam and Rowe (2002) determined that the antioxidant depletion rate increases in order with immersion in the following media: air, tap water, and high organic content leachate. Mueller and Jakob (2003) confirmed that the antioxidant depletion rate is greater with immersion in water than with air. Both Sangam and Rowe (2002) and Mueller and Jakob (2003) immersed their HDPE geomembrane samples in the immersion medium such that both side of the samples were in contact with the medium.

Mueller and Jakob (2003) observed a two-stage antioxidant depletion process with immersion in water. The two-stage process was seen to consist of initial short-term antioxidant depletion at a high rate followed by long-term antioxidant depletion at a low rate. They assume that the initial short-term depletion during their testing at 80°C was the phosphite stabilizer, which constitutes the bulk of the antioxidant, diffusing out over 200 days at a rate of 0.15 minute/month as determined by OIT measurement. They further assume that the long-term depletion during their testing at 80°C was the hindered phenols diffusing out over 2000 days at a rate of 0.015 minute/month as determined by OIT measurement. They further observed that oxidation of the polymer itself started after 5 years and that deterioration proceeded quite rapidly after oxidation began at the elevated test temperature (80°C). This was not observed in the testing conducted by Hsuan and Koerner (1998) nor Sangam and Rowe (2002), since their testing was of a much shorter duration than that of Mueller and Jakob (2003). Additionally testing by Hsuan and Koerner (1998) nor Sangam and Rowe (2002) were not conducted to antioxidant depletion as with Mueller and Jakob (2003); therefore they did not observe oxidative degradation and associated degradation of the physical and mechanical properties.

Mueller and Jakob (2003) determined that antioxidant depletion occurs over time due to diffusion out of the HDPE geomembrane and oxidative consumption within the geomembrane. It was also determined that under conditions of low temperature and low oxygen levels, diffusion is the predominant antioxidant depletion mechanism as with typical field conditions. Oxidative consumption is the predominant mechanism, under conditions of high temperature and high oxygen levels.

Hsuan and Koerner (1998) postulated that HDPE degradation due to thermal oxidation occurs in the following three stages:

- Stage A: Antioxidant depletion period,
- Stage B: Induction period, and
- Stage C: Polymer thermal oxidation period.

Koerner (1998) has additionally estimated that the induction period (i.e. the time between antioxidant depletion and onset of thermal oxidation) would last from 20 to 30 years based upon the examination of exhumed HDPE milk containers at the bottom of a landfill.

Table 11 presents the estimated antioxidant depletion times at temperatures of 33 and 40°C based upon the testing by Hsuan and Koerner (1998) and Sangam and Rowe (2002). Additionally the times based upon the methodology of Mueller and Jakob (2003) are provided utilizing the corresponding activation energies determined by Hsuan and Koerner (1998) and Sangam and Rowe (2002). In general the antioxidant depletion times estimated by the methodology of Mueller and Jakob (2003) are greater than those determined by Hsuan and Koerner (1998) and Sangam and Rowe (2002) for the same activation energies. It is likely that the antioxidant depletion times provided in Table 11 are low (i.e. conservative), since they are probably based upon activation energies associated with the initial short-term depletion of the phosphite stabilizer rather than the long-term depletion of the hindered phenols. A final item of note is the fact that the studies utilized different HDPE geomembranes with potentially different antioxidant packages. All three studies assumed that the antioxidant packages of the HDPE geomembranes they tested included phosphites and hindered phenols, however the quantity of each was unknown. The antioxidant packages are typically treated as proprietary information, by the HDPE geomembrane manufacturers, and therefore the information is not generally available to the public. Differences in the makeup of the antioxidant packages could have a significant impact on the on the estimated antioxidant depletion times derived from each study.

Table 11. Estimated Antioxidant Depletion Times

Temperature (^oC)	Hsuan and Koerner (1998) Water/Air/Sand (yrs)	Mueller and Jakob (2003) E_a = 56 kJ/mol Antioxidant Depletion Time (years)	Sangam and Rowe (2002) Air (yrs)	Mueller and Jakob (2003) E_a = 51 kJ/mol Antioxidant Depletion Time (years)
33	73.7	93.3	74.4	71.8
40	44.9	57.1	47.6	45.9
Temperature (^oC)	Sangam and Rowe (2002) Water (yrs)	Mueller and Jakob (2003) E_a = 49 kJ/mol Antioxidant Depletion Time (years)	Sangam and Rowe (2002) Leachate (yrs)	Mueller and Jakob (2003) E_a = 42 kJ/mol Antioxidant Depletion Time (years)
33	35.6	64.7	10.4	44.9
40	23.2	42.1	7.2	31.0

Needham et al. (2004) performed an extensive review of these studies and came to the following primary conclusions:

- The antioxidant depletion times of HDPE geomembranes may be significantly longer than that estimated by Hsuan and Koerner (1998) and Sangam and Rowe (2002), based upon the two-stage depletion seen by Mueller and Jakob (2003). Additionally it may also be longer due to the following:
  - The leachate strength in testing by Sangam and Rowe (2002) remained constant, whereas it will likely decrease with time and the rate of antioxidant depletion will probably also decrease with time,
  - The presence of soil particles in contact with the geomembrane in the field reduces its contact area with air, water, and/or leachate.
  - Antioxidant depletion due to oxidative consumption would be low, since only limited oxygen levels would be present due to the partially saturated or saturated surrounding materials and the reducing conditions often associated with landfills.
- Mueller and Jakob (2003) took samples for OIT measurement from the center of the geomembrane thickness, whereas Hsuan and Koerner (1998) and Sangam and Rowe (2002) tested the entire geomembrane thickness. This could have had an impact on the antioxidant depletion times estimated, since a greater concentration of antioxidants should be located in the center than at the surface over time.

- "The activation energy reflects the necessary minimum energy of the antioxidant depletion process and will depend on the characteristics of the polyethylene resin, the antioxidant package, and the exposure conditions in which the antioxidant loss is occurring." The rate of antioxidant depletion is exponentially dependent upon the activation energy. "It is tentatively inferred that the lower activation energies found by Hsuan and Koerner (1998) and Sangam and Rowe (2002) reflect faster diffusion of more easily depleted antioxidants, rather than slower diffusion of the residual antioxidants, which provide the very long-term antioxidant protection." "Values of activation energy of 60-75 kJ/mol appear a reasonable, conservative estimate."
- "As noted by Mueller and Jakob (2003), the overall rate of antioxidant loss from a geosynthetic is proportional to its surface area and the total amount of stabilizer in the geosynthetic is proportional to its volume. Thus, the antioxidant depletion time should be proportional to the thickness of the material." However due to the limited available data sets, it is not yet possible to draw quantitative conclusions with regard to geomembrane thickness.
- High initial OIT values do not necessarily result in long-term oxidation stability. For example, phosphites can produce high initial OIT values but do not greatly contribute to long-term oxidative stability at typical field temperatures. Therefore HDPE geomembrane specifications should not only stipulate an initial OIT value.
- Needham et al. (2004) believe that a reasonable estimation of the antioxidant depletion time can be derived from the following:
    - Slow long-term OIT depletion rates from Mueller and Jakob (2003),
    - Increased rate of depletion for leachate exposure found by Sangam and Rowe (2002),
    - Effects of a confined sample under compressive stress sandwiched between saturated sand and dry sand, as investigated by Hsuan and Koerner (1998), and
    - Measuring durability of the geomembrane in terms of the tensile test (but not service life as a hydraulic barrier).

4.2.4 Thermal Oxidative Degradation

Thermal oxidative degradation is the principal degradation mechanism for HDPE geomembranes in landfills (Rowe 2004). Thermal oxidative degradation of a HDPE geomembrane can begin only after the antioxidants have been depleted and only if oxygen is available. (Koerner 1998; Mueller and Jakob 2003; Needham et al. 2004). Thermal oxidative degradation is initiated with the production of free radicals ($R^\bullet$) within the polymer structure due to elevated temperatures, high energy irradiation, etc (Koerner 1998; Needham et al. 2004). If oxygen is available the free radicals rapidly combine with oxygen producing peroxide free radicals ($ROO^\bullet$). These peroxide free radicals can then react with intact portions of the polymer to form additional free radicals and hydroperoxides (i.e. oxidized polymer chains (ROOH)). The hydroperoxides can then decompose to produce additional free radicals. This progression leads to accelerated polymer chain reactions, resulting in polymeric main chain scission (i.e. breakage of covalent bonds within the polymer structure) (Koerner 1998; Koerner and Hsuan 2003; Needham et al. 2004). The following are the primary thermal oxidative degradation reactions:

$RH + \text{energy} \;\; R^\bullet + H^\bullet$

$R^{\bullet} + O_2 \rightarrow ROO^{\bullet}$
$ROO^{\bullet} + RH + \text{energy} \rightarrow ROOH + R^{\bullet}$,
where RH = polymer chain, $R^{\bullet}$ = free radical, $ROO^{\bullet}$ = peroxide free radical; ROOH = hydroperoxides (i.e. oxidized polymer chains)

Polymeric main chain scission caused by oxidation results in embrittlement of the HDPE geomembrane and degradation of its mechanical properties (Koerner and Hsuan 2003; Mueller and Jakob 2003). However, even after the HDPE geomembrane becomes brittle it remains intact and can withstand high pressure (Mueller and Jakob 2003). Oxidation only occurs in amorphous regions of an HDPE geomembrane, since oxygen can not enter the crystalline regions. Therefore the overall rate of oxidation is inversely proportional to the degree of crystallinity (Needham et al. 2004). Elevated temperatures and the presence of transition metals (e.g. manganese, copper, aluminum, and iron) increase the rate of oxidation (Needham et al. 2004). However complete oxidation of a HDPE geomembrane will take an extended period of time. It has been estimated by Albertsson and Banhidi (1980) that a 60-mil thick HDPE geomembrane would take 10,000,000 years for complete oxidation based upon a mass loss of 0.00001% per year once oxidation starts (Needham et al. 2004).

However if oxygen is not available, the production of free radicals ($R^{\bullet}$) leads to polymer crosslinking (i.e. combining polymer molecules) rather than polymer chain scission. Polymer crosslinking up to a point in general improves the mechanical properties of the HDPE geomembrane (Kresser 1957; Frados 1976; Schnabel 1981; Sangster 1993; Koerner 1998).

Based upon this information it has been concluded (Koerner 1998; Needham et al. 2004) that HDPE geomembranes in landfill service will slowly degrade by thermal oxidation. Oxidation will generally be limited by the availability of oxygen within the subsurface, and such slow oxidative degradation will not result in the disintegration or disappearance of the geomembrane within a timeframe of interest (i.e. 10,000 years). Thermal oxidative degradation is of no concern where oxygen has been removed from the surface of the geomembrane.

4.2.5 High Energy Irradiation Degradation

HDPE degradation by high energy irradiation can be similar to degradation by UV radiation (Needham et al. 2004). It has often been cited that the basic mechanical properties of a typical polymer start to change due to irradiation degradation by main chain scission at a total dose greater than 1 to 10 Mrad (Phillips 1988; Koerner et al., 1990; Koerner 1998; Nimitz et al. 2001; Needham et al., 2004). However, as discussed below, the impact of irradiation on polymers, and on high density polyethylene (HDPE) in particular, is determined primarily by the total absorbed dose and the presence or absence of oxygen.

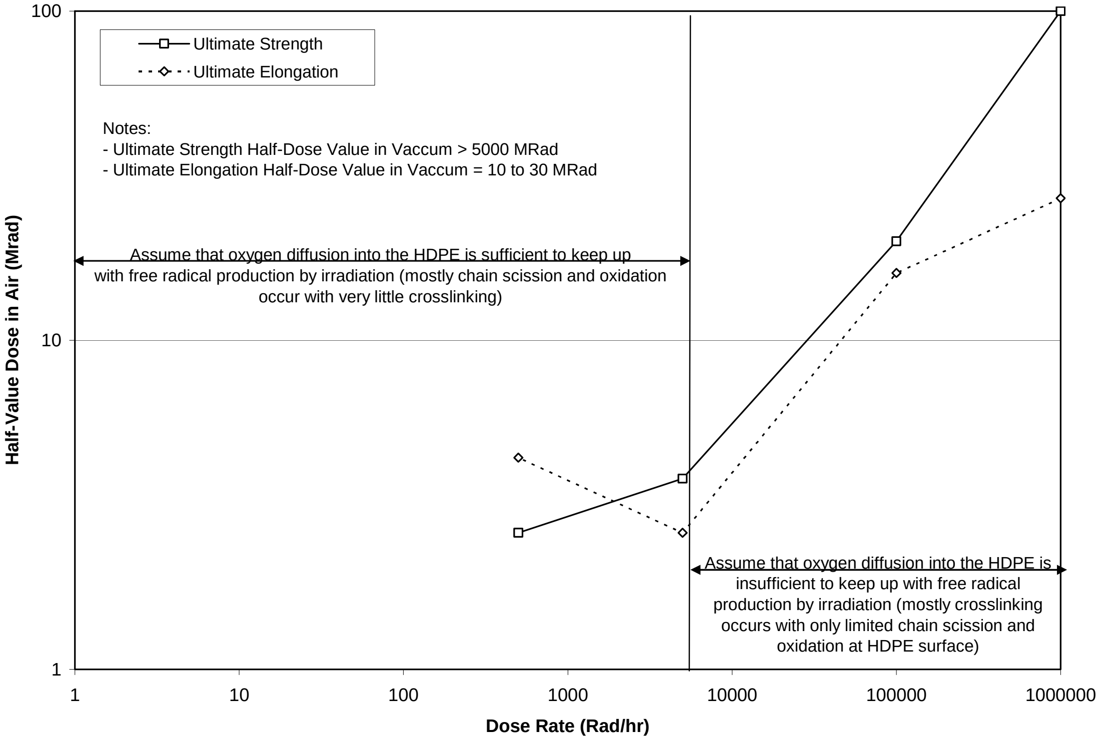
The absorption of high energy ionizing radiation such as gamma rays (γ-rays) by polymers primarily results in the production of free cation radicals and the ejection of electrons within the polymer. The ejected electrons can induce additional ionizations or produce electronic excitation in surrounding molecules. Secondary reactions can include the production of ions (both cations and anions) and free anion radicals. These products of radiation absorption are unstable and are reactive toward surrounding intact molecules resulting in both crosslinking (combining polymer molecules) and main-chain scission (breakage of polymer molecules). For polyethylene the extent of irradiation induced crosslinking or main chain scission appears to be independent of the type of radiation within a factor of 2 (i.e. alpha particles, beta particles, gamma-rays, X-rays, protons). Crosslinking predominates in the absence of oxygen and main chain scission predominates in the presence of oxygen. (Schnabel 1981; Sangster 1993; Harper 1996; Kudoh et al. 1996)

Irradiation of polyethylene in the absence of oxygen at relatively low doses (i.e. less than 10 Mrad) primarily results in crosslinking, which improves temperature and chemical resistance, increases the elastic modulus, tensile strength, and hardness, reduces the solubility, and improves the weatherability of the polyethylene (Kresser 1957; Frados 1976; Schnabel 1981; Sangster 1993). However, at high absorbed doses polyethylene becomes very hard and brittle (Kresser 1957; Kane and Widmayer 1989; Sangster 1993). For high density polyethylene (HDPE) the ultimate strength half-dose value in vacuum has been measured at greater than 5000 Mrad and the ultimate elongation half-dose value in vaccum has been measured at between 10 to 30 Mrad (Brandrup and Immergut 1989). The half-dose value is the absorbed dose required to reduce a particular mechanical property of the polymer by half under a defined environment (Brandrup and Immergut 1989). (Schnabel 1981)

However during irradiation in the presence of oxygen (i.e. in the presence of air) polyethylene undergoes predominately main-chain scission, which results in a rapid deterioration and subsequent deleterious impact upon mechanical properties. Main-chain scission can occur during reactions involving peroxyl and oxyl radicals. Since the oxidation of free cation radicals, produced during irradiation, results in peroxyl and oxyl radicals, the presence of oxygen during irradiation results in the occurrence of more main-chain scission. Additionally oxygen can react with lateral macroradicals, which would otherwise crosslink, thus reducing the occurrence of crosslinking. Finally radiation can provide the activation energy necessary for oxidation to occur, if oxygen is available. (Schnabel 1981; Sangster 1993; Sun et al. 1996; Badu-Tweneboah et al. 1999)

In the absence of oxygen the dose rate does not appear to influence the impact of irradiation on polyethylene (Brandrup et al. 1999). However in the presence of oxygen the following are two apparent dose rate effects (Schnabel 1981; Brandrup and Immergut 1989):

- High dose rates can result in the rapid depletion of oxygen within a polymer. This can result in further polymer deterioration, due to the combined effect of irradiation and oxidation which produces main-chain scission, being limited by oxygen diffusion into the polymer. In the case of polyethylene this can actually lead to increased crosslinking due to further irradiation once the interior oxygen has been depleted and an actual improvement in mechanical properties. In this case main-chain scission only occurs at the surface of the polymer where oxygen is available. This, therefore, produces an apparent dose rate effect upon polymer deterioration at high dose rates. (Brandrup et al. 1999). At low dose rates polymer deterioration due to main-chain scission produced by irradiation and oxidation is not limited by oxygen diffusion into the polymer. Therefore at these low dose rates the full impact of combined irradiation and oxidation is realized. Therefore at lower dose rates, dose rate does not appear to impact degradation due to irradiation but it appears to be dependent upon total dose and the presence of oxygen. Polymer thickness also impacts the influence of oxygen on the polymer, since the thicker the polymer the longer the diffusion path for oxygen diffusion into the polymer (Brandrup et al. 1999). Figure 6 and Table 12 provide the impact of dose rate on the half-dose values for ultimate strength and ultimate elongation of HDPE in air (Brandrup and Immergut 1989). From Figure 6 it is seen that dose rates above about 5000 Rad/hr have an apparent dose rate effect while dose rates below 5000 Rad/hr do not.



Notes:
- Ultimate Strength Half-Dose Value in Vaccum > 5000 MRad
- Ultimate Elongation Half-Dose Value in Vaccum = 10 to 30 MRad

Assume that oxygen diffusion into the HDPE is sufficient to keep up with free radical production by irradiation (mostly chain scission and oxidation occur with very little crosslinking)

Assume that oxygen diffusion into the HDPE is insufficient to keep up with free radical production by irradiation (mostly crosslinking occurs with only limited chain scission and oxidation at HDPE surface)

Figure 6. Dose Rate Impact on HDPE Ultimate Strength and Elongation Half-Value Dose in Air (Brandrup and Immergut 1989)

Table 12. Dose Rate Impact on HDPE Ultimate Strength and Elongation Half-Value Dose in Air (Brandrup and Immergut 1989)

Dose Rate (Rad/hr)	Ultimate Strength Half-Value Dose in Air (Mrad)	Ultimate Elongation Half-Value Dose in Air (Mrad)
1000000	100	27
100000	20	16
5000	3.8	2.6
500	2.6	4.4

- High dose rates can also result in an increase in the polymer's temperature. Many chemical reactions have fairly high activation energies, which can be overcome with the irradiation induced temperature increase and lead to reactions which might not otherwise occur (Brandrup et al. 1999).

Mechanical stress combined with irradiation is also known to accelerate radiation-induced degradation. (Hamilton et al. 1996).

4.2.5.1 Mitigating Irradiation Impacts on HDPE

The impacts of irradiation on HDPE can be mitigated by one or a combination of the following:

- The radiation dose rate can be lowered through the use of shielding to reduce the total dose absorbed by the HDPE over the period of concern,
- The level of oxygen to which the HDPE is exposed over the period of concern can be lowered so that the level and rate of degradation is oxygen dependent,
- Antioxidants (prevents oxidative chain reactions and scavenges free radicals) and carbon black (acts as an energy sink) can be incorporated into the HDPE to lower the impact of the presence of oxygen and radiation (Schnabel 1981; Brandrup et al. 1999),
- Thicker HDPE, such as 100 mil (2.5 mm) rather than 60 mil (1.5 mm), can be utilized to limit degradation to the surface of the sheet rather than to its interior, and/or
- Tensile stress on the HDPE can be minimized.

In most cases it is recommended that all of the mitigation means be employed.

4.2.5.2 Nuclear Regulatory Commission Recommendations

Staff from the Nuclear Regulatory Commission (NRC) recommended the following within Kane and Widmayer 1989:

> "To compensate for the uncertainties associated with the long-term performance of geosynthetics, and to provide the level of confidence that is required by federal regulations, the use of geosynthetics alone (e.g., as a low-permeability geomembrane or as a geotextile filter fabric) is not recommended by the NRC staff. However, the use of geosynthetics to complement and improve the performance of natural soils and rocks or other proven construction materials is recommended by the staff."

A "100 Mrad regulatory guideline was established to promote selection of polyethylene materials with extremely low risk of degradation under the exposure conditions expected in the high integrity containers." (Badu-Tweneboah et al. 1999)

4.2.5.3 HDPE Irradiation Examples

Several HDPE irradiation examples are provided below particularly those dealing with its use in low-level radioactive waste disposal service:

- As outlined in section 4.2.2 Whyatt and Fansworth (1990) evaluated a 60-mil HDPE geomembrane in simulated short-term (up to 120 days) chemical compatible tests with a high pH (~14) inorganic solution at 90^{o}C and subjected them to radiation doses ranging from 0.6 to 38.9 Mrad. The solution consisted predominately of the following in descending order: sodium, nitrite, nitrate, aluminum, potassium, and sulfate. With immersion in the solution and an applied radiation dose, the break strength and elongation decreased (i.e. properties degraded), while yield and puncture strengths and their associated elongations all increased (i.e. properties improved). The 38.9 dose was slightly greater than the break elongation half-dose value (see Section 4.2.5 for the definition of the half-dose value) of the HDPE geomembrane under the conditions tested. No other properties tested were near the half-dose value.

- Badu-Tweneboah et al. 1999 performed an evaluation that demonstrated that the polyethylene components of a low-level radioactive waste disposal landfill in Barnwell South Carolina would perform their intended function of containment during at least the 500-year design period. The two polyethylene components were a 60 mil HDPE geomembrane in the cover system and 3/8 inch thick Linear Medium Density Polyethylene (LMDPE) inner liners within concrete high integrity containers for the disposal of low-level radioactive waste.
- Compatibility testing was performed on the 60-mil smooth HDPE geomembrane planned for the Hanford Grout facility. HDPE samples were exposed to a dose rate of 740,000 rads per hour until a total radiation dose of 16 Mrad or 37 Mrad was reached. The total dose of 37 Mrad resulted in a greater than 25% decrease in geomembrane strength and elasticity. Then the HDPE was immersed in a 194^{o}F solution with a pH of 9.2 and a concentration of inorganics of 368,336 mg/L. It was stated that under these conditions the HDPE showed no unacceptable effects. (INEEL 2004)
- Traditional radiation sterilization of polymers for medical implants is performed to a dose of 2.5 Mrad (Deng et al. 1996).

4.2.6 Tensile Stress Cracking Degradation

After the antioxidants in a HDPE geomembrane have been depleted, thermal oxidation of the geomembrane commences if oxygen is present causing embrittlement and degradation of mechanical properties over time. However the geomembrane will remain an effective hydraulic barrier unless it is physically damaged or develops holes or cracks. Holes or cracks can develop from the following two types of tensile stress cracking in a HDPE geomembrane (Needham et al. 2004):

- Ductile tensile failure is a ductile failure where the applied tensile stress exceeds the short-term tensile break strength of the geomembrane, and
- Brittle stress cracking is a brittle failure where the applied long-term tensile stress is less than the short-term tensile break strength of the geomembrane.

In general, HDPE geomembrane installations should be designed so that the short-term tensile break strength of the geomembrane is not exceeded. However subgrade settlement and geomembrane downdrag by waste settlement on the side slopes can occur and cause exceedance of the geomembrane’s tensile break strength. (Needham et al. 2004)

Brittle stress cracking, on the other hand, can occur as oxidation of the HDPE geomembrane proceeds and causes increased embrittlement and degradation of its mechanical properties over time. As thermal oxidation proceeds brittle stress cracking will occur where the geomembrane is under stress at lower and lower stresses over time. However as cracking occurs stresses are relieved thus reducing the likelihood of further cracking. Brittle stress cracking can be exasperated by elevated temperatures and contact with agents such as detergents, alcohols (e.g. methanol, ethanol, and propanol), acids and chlorinated solvents (i.e. environmental stress cracking). The extent of brittle stress cracking is dependent upon the geomembrane stress crack resistance (SCR), the local and global stress over the geomembrane, the geomembrane temperature, the fluid in contact with the geomembrane, and the extent of thermal oxidative degradation. However as long as the geomembrane is not subjected to tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact, for practical considerations, indefinitely. (Needham et al. 2004)

4.2.7 Biological Degradation

Limited investigations have been performed relative to the biological degradation of HDPE geomembranes. Biological degradation of HDPE geomembranes could potentially be caused microbial biodegradation, root penetration, or burrowing animals. Koerner (1998) stated that the high-molecular-weight polymers used for geomembranes seem insensitive to microbial (i.e. fungi or bacteria) biodegradation. An investigation conducted by Serrato (2004) showed that roots from overlying pine trees turned horizontally and followed along the top of the geomembrane upon reaching a HDPE geomembrane without damaging or penetrating it. Badu-Tweneboah et al. (1999) confirm this with their statement that roots are not likely to penetrate an intact geomembrane, they are likely to develop laterally above the geomembrane, and they are not known to enlarge existing geomembrane defects. Very little information is available relative to the potential for geomembrane damage due to burrowing animals. A geomembrane would have to be harder than the burrowing animals' teeth or claws to avoid the potential for damage. Therefore geomembranes are potentially vulnerable to burrowing animals. Logically it is assumed that stronger, harder, and thicker geomembranes are more resistant to burrowing animals. (Koerner 1998)

4.3 Environment Agency Degradation Model

Based upon an extensive literature of HDPE geomembrane degradation mechanisms, Needham et al. (2004) has produced a long-term degradation HDPE geomembrane degradation model for use by the Environment Agency of England and Wales in the preparation of Performance Assessments (PA) for landfill. Needham et al. (2004) tie all degradation mechanisms to the generation of holes or cracks in the HDPE geomembrane through time. From this they have produced a six-stage model for generation of holes over time. They take generation of holes from initial installation of the geomembrane to long-term generation of holes as the geomembrane becomes increasingly more susceptible to brittle stress cracking. The following are the six stages considered by Needham et al. (2004):

- Stage 1 is the period of disposal facility construction and considers the holes produced by construction.
- Stage 2 is the operational period and considers the holes produced by waste placement.
- Stage 3 is a 10 to 50 year period immediately following closure cap construction during which no additional holes are assumed to be produced.
- Stage 4 is a combination of the antioxidant depletion and induction periods during which holes are assumed to be produced at low rates relative to subsequent stages due to tensile stresses.

- Stage 5 is the oxidation stage, which is assumed to last 50 years, during which embrittlement and further stress cracking will occur relatively rapidly due to any significant remaining tensile stress.
- Stage 6 is the terminal stage, during which it is assumed that the total number of holes present at the end of Stage 5 are reproduced as new holes every 100 years.

For each of the stages Needham et al. (2004) the generation of holes is divided into an excellent, good, and fair case with the number of holes produced increasing from the excellent to fair case. They also provide different hole sizes divided into the categories of pin holes, holes, tears, and cracks. The model produced by Needham et al. (2004) is based upon the most current research conducted concerning HDPE geomembrane degradation. They have converted that research into a form (i.e. generation of holes over time) that can be utilized in Performance Assessment (PA) contaminant transport modeling.

5 HDPE IN SALTSTONE SERVICE

HDPE geomembrane utilization in Saltstone service has been evaluated within this section. The Saltstone characteristics presented in Section 3.0 have been compared to the HDPE geomembrane degradation mechanisms presented within Section 4.2.

5.1 General Saltstone Vault #2 Overview

An evaluation of options for the configuration of Vault #2 has resulted in the selection of a cylindrical vault configuration (Hayes 2005b). The cylindrical Vault #2, which is currently in the conceptual design phase, is being designed to contain Saltstone produced from Low Curie Salt (LCS) Solution. The LCS solution, which is produced from the DDA process (see Section 3.1), is assumed to contain 0.2 curies/gallon of cesium-137 with a total curie content of 0.52 curies/gallon (Hayes 2005a). The salt solutions produced from later salt solution treatment processes will have significantly lower curie contents than the LCS. The future vaults will receive Saltstone produced from the lower curie content salt solutions.

Due to its Saltstone curie loading, Vault #2 must be built below grade as shown in Figure 7 for shielding purposes. Future vaults that will contain Saltstone with lower curie loadings can be built above grade. Vault #2 is preliminarily assumed to consist of the following (see Figure 7):

- A cylindrical concrete vault with the concrete floor, sides, and roof a minimum 8-inch thick.
- A 100-mil HDPE geomembrane and a 0.2-inch geosynthetic clay liner (GCL) or equivalent incasing the outside of the vault concrete floor and sides.
- Backfill around the sides of the vault

During operations the vault roof will not have an overlying HDPE geomembrane or GCL. However at final closure a HDPE geomembrane and GCL will be installed on top of the vault roof.

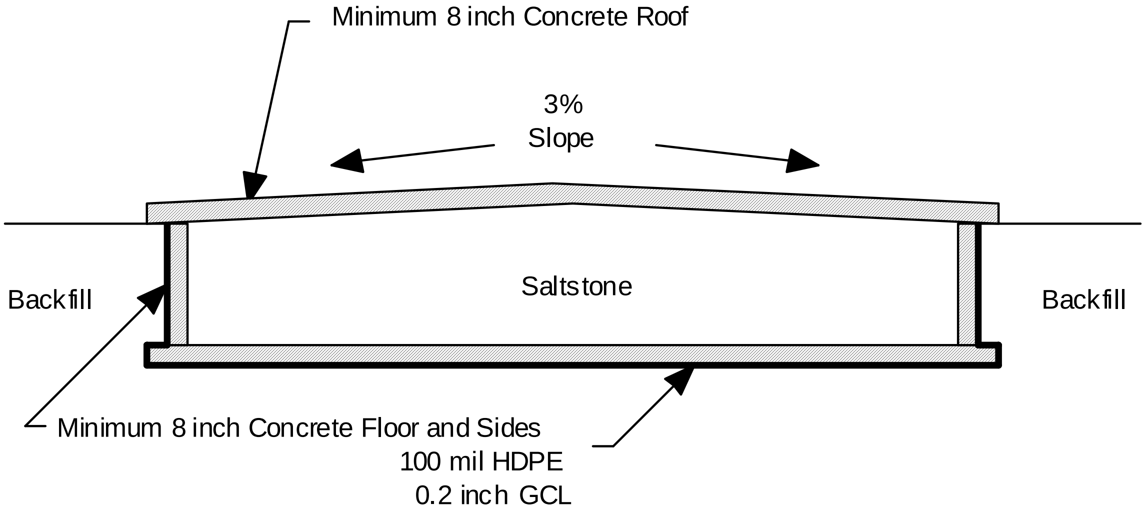


Figure 7. Preliminary Vault #2 Configuration

5.2 Ultraviolet (UV) Impacts

As indicated in Section 4.2.1 UV radiation is not considered a significant degradation mechanism for short-term exposures associated with construction, where the geomembrane is covered in a timely manner (i.e. less than several years). The Vault #2 HDPE geomembrane will be covered with a GCL or equivalent and backfill as part of the construction processes. The HDPE geomembrane will be exposed to sunlight for significantly less than a year. For future vaults, which are built above grade, the side HDPE geomembrane will not be placed on the vault until final closure; therefore no significant UV exposure will be experience by the HDPE geomembranes for these future vaults either. Based upon these considerations UV degradation is considered an insignificant degradation mechanism associated with HDPE geomembrane usage on Saltstone vaults.

5.3 Chemical Impacts

As indicated in Section 4.2.2 HDPE geomembranes can be negatively impacted by high concentrations of some organic compounds, solutions containing transition metals such as copper, manganese, and iron, and strong oxidizers (Needham et al. 2004; Rowe and Sangam 2002; and GSE 2004). Saltstone is a mixture of blast furnace slag, flyash, cement or lime, and salt solution, which chemically react to form an alkaline, reducing, micro-porous, cementitious matrix, consisting of solids such as calcium aluminosilicate and containing a solution of salts within its pore structure (Saltstone pore fluid). The pore fluid consists predominately of sodium, nitrate, and nitrite (see Section 3.3). While the salt solution may contain relatively low concentrations of predominately volatile organics, the elevated temperatures experienced during heat of hydration and radioactive decay (see section 3.4) will tend to drive off the volatile organics results in minimal concentrations within the pore fluid. While the salt solution may contain transition metals, it is unlikely that the pore fluid will contain any significant concentration of transition metals, since the metals are typically insoluble under the alkaline, reducing conditions of Saltstone. The blast furnace slag produces reducing conditions within the Saltstone therefore there are no strong oxidizers within Saltstone.

Based upon a significant number of independent studies on leachate effects on HDPE geomembranes, HDPE manufacturers’ have compiled chemical resistance charts which are generally reliable (Koerner 1998). Table 13 provides excerpts from the HDPE chemical resistant chart produced by GSE Lining Technology, Inc. compared to the primary soluble salts contained in salt solution. As seen in Table 13, HDPE is considered chemically resistant to all of these salts.

Table 13. Chemical Resistance to Primary Salt Solution Soluble Salts (GSE 2004)

Primary Soluble Salts in the Salt Solution	Concentration	Chemical Resistance at 60°C
Sodium nitrate	Saturated solution	Satisfactory
Sodium hydroxide	Saturated solution	Satisfactory
Sodium nitrite	Saturated solution	Satisfactory
Sodium aluminum hydroxide ($NaAl(OH)_4$) [1]	Not listed	Not listed
Sodium carbonate	Saturated solution	Satisfactory
Sodium sulfate	Saturated solution	Satisfactory

[1] Aluminum chloride, aluminum fluoride, and aluminum sulfate are all listed as having satisfactory chemical resistance to saturated solutions of these compounds at 60°C. (www.gseworld.com/Literature/TechnicalNotes/PDF/TN032ResistChart.pdf)

Additionally Whyatt and Fansworth (1990) and INEEL (2004) have performed studies on the compatibility of HDPE geomembranes to solutions similar to the Saltstone salt solution. Both these studies determined that HDPE geomembranes were chemically compatible with the high pH, inorganic solutions, which they evaluated.

On these bases, it has been determined that HDPE geomembranes are chemically compatible with Saltstone and its pore fluid.

5.4 Temperature Impacts

The temperatures associated with Saltstone heat of hydration and radioactive decay will primarily impact the antioxidant depletion and subsequent thermal oxidative degradation of any HPDE geomembrane utilized in Saltstone service. As outlined in Section 3.4, Appendix A provides the average yearly temperature data adjacent to the Saltstone and 1-foot below the Saltstone over a 199-year period. These data form the basis for evaluating the temperature impacts of Saltstone on HDPE geomembranes.

5.4.1 Saltstone Temperature Impacts on Antioxidant Depletion

Antioxidant depletion is highly temperature dependent, and the heat of hydration and radioactive decay associated with Saltstone result in higher than ambient temperatures in the vicinity of the Saltstone (see Section 3.4). As indicated in 4.2.3.4, the temperature dependent, the two-stage antioxidant depletion seen by Mueller and Jakob (2003) is considered more representative of actual antioxidant depletion than the results produced by Hsuan and Koerner (1998) and Sangam and Rowe (2002). The work of Mueler and Jakob (2003) resulted in the following equation for the estimation of antioxidant time of depletion (see Section 4.2.3.3):

$$t_1(T) = 5\ yrs\ e^{\frac{E_a}{8.319\ J/mol\ K}\left[\frac{1}{T} - \frac{1}{353.15\ K}\right]},$$

where $t_1(T)$ = antioxidant depletion period in years at the ambient temperature of the HDPE; E_a = depletion process activation energy; T = ambient temperature of the HDPE in K (K = 273.15 + °C)

In order to determine the antioxidant time of depletion for any given average temperature, the appropriate depletion process activation energy must be determined. As outlined in

Section 4.2.3.3 the activation energy is dependent upon the medium within which the HDPE geomembrane is immersed. One side of a HDPE geomembrane in Saltstone service could come into contact with the Saltstone pore fluid, which is an alkaline, reducing, salt solution, consisting predominately of sodium, nitrate, and nitrite with a very low organic content (see Section 3.3). The other side of the HDPE would be in contact with a nearly 100% water saturated GCL. Due to this condition, an activation energy associated with immersion in water is considered most applicable. Activation energy associated with immersion in synthetic leachate per Sangam and Rowe (2002) is not considered applicable, since their synthetic leachate had a high organic content, which facilitated antioxidant diffusion, and the Saltstone pore fluid does not have a similarly high organic content. From Table 9 depletion process activation energies associated with immersion in water from 42 to 100 kJ/mol were documented. However the Hsuan and Koerner (1998) and Sangam and Rowe (2002) activation energies of Table 9 reflect primarily the initial short-term antioxidant depletion at a high rate and do not take into account the succeeding long-term antioxidant depletion at a low rate. Based upon this, Needham et al. (2004) concluded that, “Values of activation energy of 60-75 kJ/mol appear a reasonable, conservative estimate.” Therefore for determination of a conservative antioxidant time of depletion for a HDPE geomembrane in Saltstone service, an activation energy of 60 kJ/mol will be utilized. Using Mueler and Jakob’s (2003) equation (see above) and an activation energy of 60 kJ/mol, it has been estimated that a HDPE geomembrane in Saltstone service would have a conservative antioxidant time of depletion of at least 90 years (see Appendix B for the calculation). This estimate is considered conservative for the following reasons:

- The activation energy utilized is at the low end of that recommended,
- The estimate does not take into account that the HDPE geomembrane will be surrounded by concrete and bentonite and that the antioxidant will not diffuse through the solids, and
- Antioxidant depletion due to oxidative consumption would be low, since only limited oxygen levels would be present.

The 90 year antioxidant time of depletion is only applicable to the HDPE geomembranes on the side and bottom of Vault #2, which will be built below grade. The geomembrane on top of Vault #2 will not be emplaced until final closure of the entire SDF. Future vaults will be built above grade and will not have the side HDPE geomembrane installed on the vault until final closure. These factors mean that the antioxidant time of depletion for the geomembrane on top of Vault #2 and these future vaults will be much greater than for Vault #2, since the average temperature of their HDPE geomembranes will be much less than that of Vault #2.

5.4.2 Saltstone Temperature Impacts on Thermal Oxidative Degradation

As indicated in Section 4.2.4, thermal oxidative degradation of a HDPE geomembrane can begin only after the antioxidants have been depleted, only if oxygen is available, and increases with temperature. (Koerner 1998; Mueller and Jakob 2003; Needham et al. 2004). Based Section 5.4.1, the antioxidants of a HDPE geomembrane in Vault #2 Saltstone service would be depleted after 90 years. Therefore only after 90 years could thermal oxidative degradation of the HDPE geomembrane begin. At 90 years the HDPE geomembrane temperature would be approximately 30.5°C and declining (see Appendix A). Needham et al. (2004) states a reasonable long-term average temperature for “wet” landfills is estimated to be between 30 and 35°C, and for "dry" landfills to be between 15 and 20°C. The temperature, of a Saltstone HDPE geomembrane after antioxidant depletion, falls within the range of temperatures considered by Needham et al. (2004) for their HDPE geomembrane degradation model. Therefore from a temperature standpoint their degradation model is applicable to the Saltstone vaults.

The other requirement for thermal oxidative degradation to proceed is the availability of oxygen. Oxygen on the interior side of the HDPE geomembrane toward the Saltstone will be extremely limited since the Saltstone is reducing and oxygen will be consumed by the Saltstone itself. Oxygen on the exterior side of the HDPE geomembrane adjacent to the GCL or equivalent will be limited by the water solubility of oxygen and the water diffusivity of oxygen since the bentonite should be near 100% saturation. Due to this limited availability of oxygen, thermal oxidative degradation of a HDPE geomembrane in Saltstone service should be very slow. This is also consistent with the degradation model presented by Needham et al. (2004).

The Vault #2 side and bottom HDPE geomembranes will experience a greater long-term average temperature than that on top of Vault #2 or of future vaults. Therefore the thermal oxidative degradation of the Vault #2 side and bottom HDPE geomembranes will proceed somewhat more rapidly than for the top of Vault #2 and future vaults. This temperature variation is due to Vault #2 being built below grade and having its side and bottom HDPE geomembranes installed prior to pouring Saltstone.

5.5 Irradiation Impacts

The dose rates associated with Saltstone as shown in Table 1 are significantly below the 5000 Rad/hr dose rate above which an apparent dose rate effect in HDPE is seen (see Section 4.2.5). Therefore Saltstone’s irradiation impact upon HDPE is assumed to be due to only total dose and not dose rate. From Table 12 the HDPE ultimate strength half-value dose in air at a dose rate of 500 Rad/hr was 2.6 Mrad (Brandrup and Immergut 1989). The basic mechanical properties of a typical polymer start to change due to irradiation degradation at a total dose greater than 1 to 10 Mrad (Phillips 1988; Koerner et al., 1990; Koerner 1998; Nimitz et al. 2001; Needham et al., 2004), with levels as high as 100 Mrad being listed as acceptable (Badu-Tweneboah et al. 1999). Therefore a total dose of 2.6 Mrad appears to be a reasonable limit for total dose to HDPE utilized as part of the diffusion barrier within the Saltstone Disposal Facility (SDF). Table 14 provides the time until the 2.6 Mrad total dose limit is reached for various thicknesses of concrete shielding. The time was calculated two ways: 1) assuming no radioactive decay; 2) assuming all activity is due to Cs-137 and providing radioactive decay based upon Cs-137’s 30.07 year half-life. Based upon these calculations, shielding equivalent to 4 to 10-inches of concrete will be satisfactory to maintain the total dose to HDPE geomembranes in Saltstone service to less than 2.6 Mrad over 10,000 years. This total dose to the geomembrane must be verified once the Vault #2 conceptual design has been determined. Appendix C provides the total dose calculations. The dose rate experienced by geomembranes on future vaults will be much less than that of geomembranes on Vault #2.

Table 14. Time until Total Dose of 2.6 Mrad Reached

Concrete Thickness (inches)	Dose Rate at Time Zero for Saltstone made from 0.2 Ci/gal Cs-137 Salt Solution (rad/hr)	Time until 2.6 Mrad Reached - No Radioactive Decay Considered (years)	Time until 2.6 Mrad Reached – Assume all Cs-137 Decay (years)
0	1.10E+01	27.0	<50
2	6.23E+00	47.6	<250
4	2.73E+00	108.8	>>10,000
6	1.19E+00	248.5	>>10,000
8	5.22E-01	567.8	>>10,000
10	1.62E-01	1,833.7	>>10,000
12	1.13E-01	2,619.4	>>10,000
14	5.75E-02	5,161.7	>>10,000
16	3.64E-02	8,140.0	>>10,000

5.6 Tensile Stress Cracking Impacts

As outlined in Section 4.2.6 ductile tensile failure of HDPE geomembranes will occur wherever the applied stress exceeds the short-term tensile-break-strength of the geomembrane. However, due to the generally vertical and horizontal orientation of the HDPE geomembrane on the Saltstone vaults (see Figure 7), the geomembrane should be able to be designed to minimize the applied tensile stress. Additionally, downdrag by waste settlement, which increases tensile stresses within typical landfills, is not applicable in the case of Saltstone, since it is a cementitious waste form and since it is planned to apply the geomembrane externally to the cylindrical concrete vault containing the Saltstone. Therefore ductile tensile failure of the HDPE geomembrane in Saltstone service is not considered likely.

However as also outlined in Section 4.2.6, thermal oxidation of the HDPE geomembrane will commence after its antioxidants have been depleted (after approximately 90 years per Section 5.4.1) if oxygen is present. This thermal oxidation will cause embrittlement and degradation of the geomembrane mechanical properties over time making the geomembrane more susceptible to brittle stress cracking. Additionally thermal oxidation is exasperated by irradiation if sufficient oxygen is present (see Section 4.2.5) and elevated temperatures (see Section 4.2.4). The impact of irradiation will be somewhat mitigated by the limited supply of oxygen to the HDPE geomembrane in Saltstone service (see Section 5.4.2). Temperature will only impact thermal oxidation after the antioxidants are depleted at 90 years when the temperature of the geomembrane due to the Saltstone will be similar to that of typical landfills considered by Needham et al. (2004) for their HDPE geomembrane degradation model (see Section 5.4.2).

As thermal oxidation proceeds brittle stress cracking will occur where the geomembrane is under stress at lower and lower stresses over time. However as cracking occurs stresses are relieved thus reducing the likelihood of further cracking. The extent of brittle stress cracking is dependent upon the geomembrane stress crack resistance (SCR), the local and global stress over the geomembrane, the geomembrane temperature, the fluid in contact with the geomembrane, and the extent of thermal oxidative degradation. HDPE geomembranes in Saltstone service will be specified to have a minimum SCR of 300 hours as required by GRI (2003) and will be designed to minimize tensile and shear stress. Therefore as long as the geomembrane is not subjected to excessive tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact, for practical considerations, indefinitely (Needham et al. 2004). As indicated above the geomembrane temperature during the period of thermal oxidation will be similar to that of typical landfills considered by Needham et al. (2004). The Saltstone pore fluid (see Section 3.3) and vadose zone water which will come into contact with the geomembrane does not contain significant quantities of the agents which exasperate brittle stress cracking (see Section 4.2.6). Conditions for future vaults, which are not installed in the subsurface initially, will be even better than that of Vault #2 relative to the minimization of brittle stress cracking.

Based upon this evaluation it is clear that HDPE geomembranes in Saltstone service fall within the bounds of the HDPE geomembrane degradation model produced by Needham et al. (2004). Since Saltstone service includes potential negative impacts to the HDPE geomembrane from irradiation, it is recommended that the model’s fair case for the generation of holes be utilized to represent HDPE geomembranes in Saltstone service.

5.7 Biological Impacts

As stated in Section 4.2.7 HDPE geomembranes in general are insensitive to microbial biodegradation and root penetration (Koerner 1998; Badu-Tweneboah et al. 1999; Serrato 2004) and are therefore not considered as degradation mechanism for HDPE geomembranes in Saltstone service. The only potential biological degradation mechanism for HDPE geomembranes is damage due to burrowing animals. However in the case of the Saltstone service damage due to burrowing animals is not considered feasible, since the HDPE geomembranes will be covered with a minimum 13-foot thick closure cap which includes a 1-foot thick erosion barrier. The erosion barrier will consist of 2 to 6-inch granite stone filled with Flowable Fill (Phifer and Nelson 2003).

5.8 Summary of Anticipated Degradation Mechanism Impacts

The following is a summary of the anticipated impacts of the degradation mechanisms upon HDPE geomembranes in Saltstone service:

- Since HDPE geomembranes in Saltstone service will only be exposed to UV radiation during construction, UV degradation is considered an insignificant degradation mechanism (see Section 5.2).
- HDPE geomembranes are chemically compatible with Saltstone and its pore fluid, therefore chemical impacts on geomembranes in Saltstone service are considered insignificant (see Section 5.3)
- It is estimated that due to the elevated temperatures associated with Saltstone heat of hydration and radioactive decay, the antioxidants in the HDPE geomembranes located on the sides and bottom of Saltstone Vault #2 will be depleted within approximately 90 years. It will take significantly longer to deplete the antioxidants in the HDPE

geomembrane placed on top of Vault #2 and that utilized in future vaults. (see Section 5.4.1)
- Thermal oxidative degradation of HDPE geomembranes in Saltstone service will occur after antioxidant depletion but should be very slow due to oxygen limitations. Thermal oxidative degradation will occur even more slowly for the HDPE geomembrane placed on top of Vault #2 and that utilized in future vaults than for that located on the sides and bottom of Saltstone Vault #2. Such degradation is considered consistent with the degradation model presented by Needham et al. (2004). (see Section 5.4.2)
- It is assumed that shielding equivalent to 4 to 10-inches of concrete for Vault #2 will be satisfactory to maintain the total dose to HDPE geomembranes in Saltstone service to less than 2.6 Mrad over 10,000 years and that this is a reasonable limit to minimize the irradiation impact on the HDPE geomembrane. The total dose to the HDPE geomembranes of future vaults will be significantly less than that of Vault #2 assuming the same concrete thickness. The projected total dose to the geomembrane needs to be verified for Vault #2 once the conceptual design has been completed. (see Section 5.5)
- Brittle stress cracking of HDPE geomembranes in Saltstone service will occur over time, after the antioxidants have been depleted (estimated at 90 years), as thermal oxidation causes geomembrane embrittlement and mechanical property degradation. This process allows brittle stress cracking to occur at lower and lower stresses over time, however this is somewhat offset by the stress relief that is provided to intact areas due to adjacent cracking. As long as the geomembrane is not subjected to excessive tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact, for practical considerations, indefinitely (Needham et al. 2004). Based upon this evaluation it is clear that HDPE geomembranes in Saltstone service fall within the bounds of the HDPE geomembrane degradation model produced by Needham et al. (2004). Brittle stress cracking will occur even more slowly for the HDPE geomembrane utilized in future vaults than that utilized for Vault #2.
- Microbial biodegradation, root penetration, and burrowing animals are considered insignificant degradation mechanisms for HDPE geomembranes in Saltstone service (see Section 5.7).

In summary, antioxidant depletion of HDPE geomembranes installed on Vault #2 prior to pouring Saltstone into the vault will occur after approximately 90 years. After antioxidant depletion, thermal oxidation of the HDPE geomembranes will occur very slowly due to oxygen limitations. Thermal oxidation will be slightly exasperated due to irradiation, however irradiation will be minimized to acceptable levels by shielding the HDPE geomembranes with 4 to 10 inches of concrete. As thermal oxidation causes geomembrane embrittlement and mechanical property degradation, brittle stress cracking will occur at lower and lower stresses over time. However stress relief is provided to intact areas by adjacent cracking and as long as the geomembrane is not subjected to excessive tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact, for practical considerations, indefinitely (Needham et al. 2004). Therefore it is anticipated that the bulk of the HDPE will remain intact and functioning as a diffusion barrier for a very long period of time. The HDPE geomembrane degradation model produced by Needham et al. (2004) should adequately describe the formation of holes over time in the Vault #2 geomembrane. The same degradation processes should occur for the geomembranes on top of Vault #2 and on future vaults, but at a slower rate than for Vault #2.

6 ESTIMATED GROUNDWATER NITRATE/NITRITE CONCENTRATIONS

Conservative estimates of the nitrate groundwater concentrations resulting from the Vault #2 cylindrical concept with and without a 100-mil HDPE geomembrane have been made for years 100, 1,000, and 10,000. The estimates are based upon steady-state conditions and the assumed vault configuration shown in Figure 8. This vault configuration assumes that the side and bottom HDPE geomembranes are on the inside of the vault since this greatly simplifies the calculation by allowing the assumption of flushing boundary conditions on the outside of the concrete (i.e. nitrate concentration of 0 at the concrete-soil boundary due to water flux which transports all nitrate away). The nitrate groundwater concentrations have been estimated per the methodology outlined below.

- Vault #2 has been analyzed as a 154-foot inside diameter, minimum 20-foot high cylinder made out of concrete a minimum 8-inch thick and 100-mil HDPE covered with a closure cap consistent with that outlined within Phifer and Nelson (2003).
- HDPE degradation has been analyzed over time consistent with the "fair" case degradation outlined by Needham et al. (2004).
- Vault concrete and Saltstone degradation has been analyzed over time as outlined by Cook (2004).
- The HELP model (USEPA 1994a and USEPA 1994b) has been used to estimate the flux of water through and around the Cylindrical Vault.
- The water flux out the bottom of the Cylindrical Vault has been analyzed assuming that the nitrate concentrations are equal to that of the Saltstone pore fluid (i.e. 47,234 mg/L nitrate/nitrite as nitrogen (WSRC 2002)). Diffusion has not been considered out the bottom.
- The water flux around the Cylindrical Vault has been analyzed assuming it contains nitrate due to diffusion out the side of the vault. Advection has not been considered out the sides.
- The nitrate concentration has been analyzed for a monitoring well with a screen length of 10 feet and compared to the nitrate maximum contaminant level of 10 mg/L of nitrate as nitrogen. The nitrate concentration within the 10-foot screen interval has been estimated by determining the mass of nitrate that enters a 20-foot by 2500-foot area (50,000 ft^2) per a given time period divided by the volume of water that enters the area over the same given time period. It is assumed that this 50,000 ft^2 feeds the 10-foot screen interval.

Table 15 provides the estimated nitrate groundwater concentrations for years 100, 1,000, and 10,000 determined utilizing this methodology. Appendix D provides the detailed nitrate groundwater concentration calculations. As seen in Table 15 the use of the HDPE geomembrane in combination with the concrete greatly enhances the protection provided over concrete alone, particularly over the first 1000 years. At year 100 it is estimated that the combination is over 200,000 times more effective than concrete alone, and at year 1,000 it is estimated to be approximately 6 times more effective. Additionally none of the estimated concentrations for a single vault exceeded the Maximum Contaminant Level of 10 mg/L, even for concrete alone. Although the concrete alone at year 100 came close at an estimated concentration of 6.2 mg/L. Further these calculations are considered conservative as outlined in Appendix D, particularly since the Saltstone itself is always assumed to contain 47,234 mg/L nitrate throughout its mass regardless of time.

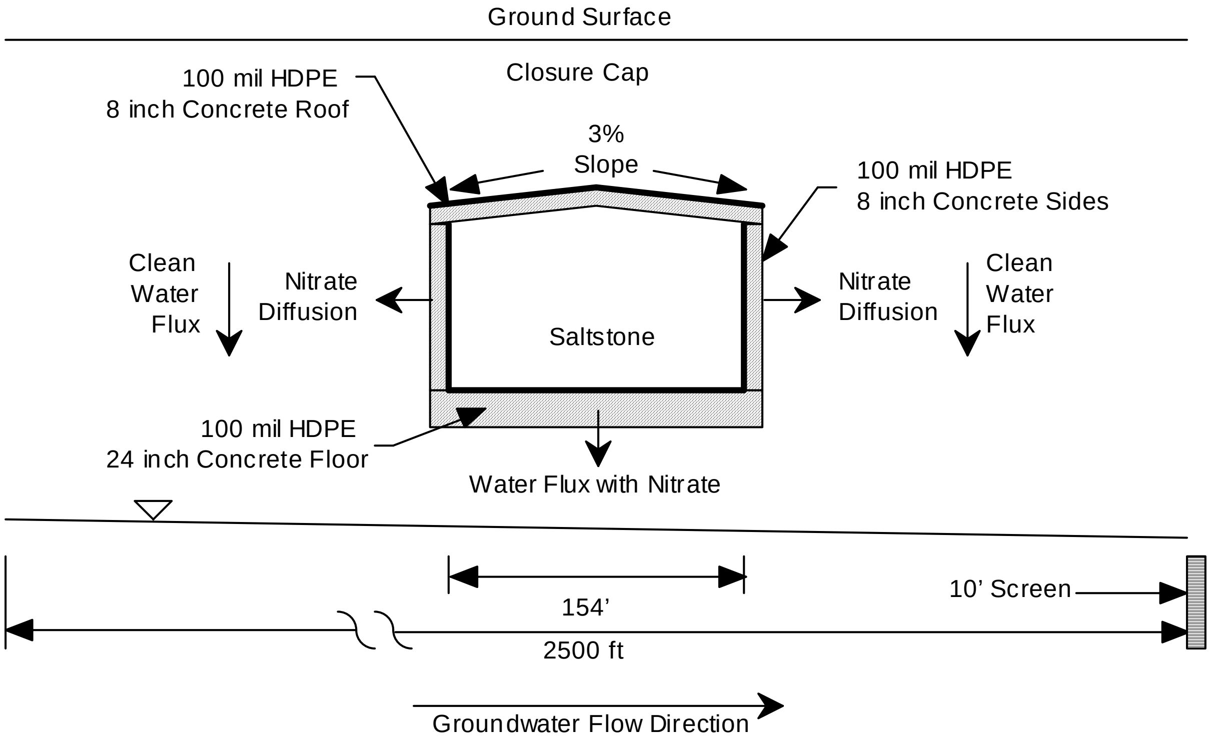


Figure 8. Assumed Vault #2 Configuration for Nitrate Groundwater Estimations

Table 15. Estimated Nitrate Groundwater Concentrations

Year	Maximum Contaminant Level (mg/L, nitrate as nitrogen)	Nitrate in Well for Vault without HDPE (mg/L, nitrate/nitrite as nitrogen)	Nitrate in Well for Vault with HDPE (mg/L, nitrate/nitrite as nitrogen)	Ratio of Nitrate for Vault without HPDE to with HDPE
100	10	6.2	2.87E-05	216,027.9
1,000	10	0.25	0.044	5.7
10,000	10	3.12	2.8	1.1

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The evaluation of the use of High density polyethylene (HDPE) geomembranes in Saltstone service has resulted in a conceptual understanding of the potential HDPE geomembrane degradation in such service. The following HDPE degradation mechanisms were considered: ultraviolet (UV) radiation, chemical, antioxidant depletion, thermal oxidation, high energy irradiation, tensile stress cracking, and biological. It was determined that ultraviolet (UV) radiation, chemical, and biological degradation mechanisms were insignificant for HDPE geomembranes in Saltstone service. For HDPE geomembranes utilized on Vault #2 it was estimated that antioxidant depletion would occur after approximately 90 years, primarily due to the elevated temperatures during that time frame. After antioxidant depletion, thermal oxidation of the HDPE geomembranes will occur very slowly due to oxygen limitations. Thermal oxidation will be slightly exasperated due to irradiation, however it is recommended that irradiation will be minimized to acceptable levels (less than 2.6 Mrad over 10,000 years) by shielding the HDPE geomembranes with 4 to 10 inches of concrete. As thermal oxidation causes geomembrane embrittlement and mechanical property degradation, brittle stress cracking will occur at lower and lower stresses over time. However stress relief is provided to intact areas by adjacent cracking and as long as the geomembrane is not subjected to excessive tensile or shear stresses, it should not fragment and disintegrate, but it should remain intact, for practical considerations, indefinitely (Needham et al. 2004). Therefore it is anticipated that the bulk of the HDPE will remain intact and functioning as a diffusion barrier for a very long period of time. The same degradation processes should occur for the geomembranes on future vaults, but it should occur at a slower rate than for Vault #2, since the HDPE geomembrane temperatures will be lower on future vaults. It has also been determined, based upon this evaluation, that the HDPE geomembrane degradation model produced by Needham et al. (2004) should adequately describe the formation of holes over time in HDPE geomembranes in Saltstone service (i.e. on Vault #2 and on future vaults).

In addition to evaluating the degradation of HDPE geomembranes in Saltstone service, conservative estimations of the nitrate groundwater concentrations resulting from Saltstone disposal within an eight inch thick concrete cylindrical vault with and without a 100-mil HDPE liner indicate that the use of HDPE greatly reduces the nitrate groundwater concentrations over the first few thousand years. It has been estimated that for the first few hundred years the nitrate concentrations resulting from a concrete vault with HDPE is up to five orders of magnitude less than that without HDPE. The improvement over time decreases until at 10,000 years the concrete vault with HDPE is estimated to be only slightly better than concrete alone. However the benefit of HDPE is to slow the release of nitrate over time, significantly reduce the peak flux of nitrate out of the vault, and significantly reduce the peak nitrate groundwater concentration. These nitrate estimates were made utilizing the Needham et al. (2004) HDPE geomembrane degradation model.

As a result of evaluating the degradation of HDPE geomembranes in Saltstone service and estimating nitrate groundwater concentrations resulting from the Vault #2 cylindrical concept, it has been determined that the use of HDPE geomembranes as part of the disposal concept could significantly enhance Saltstone confinement. On this basis it has been concluded that the PA can probably justify taking credit for a HDPE geomembrane as one component of a multi-component diffusion barrier. The PA should present degradation of the system over time, and the model produced by Needham et al. (2004) could be used as the basis for this degradation.

7.2 Recommendations

Based upon this evaluation the following primary recommendations are made regarding the use of HDPE geomembranes in Saltstone service:

- It is recommended that a minimum 100 mil (2.5 mm) thick HDPE geomembrane formulated with long-term, low-temperature antioxidants and carbon black be specified as outlined in the material requirements section of Table 16. A thick HDPE geomembrane is required due to the duration of required service (i.e. 10,000 years) and the service conditions (radiation and thermal).
- It is recommended that HDPE geomembranes should be utilized as one component of a multi-component diffusion barrier, consisting of a geosynthetic clay liner (GCL), HDPE geomembrane, and concrete as outlined in the design requirements section of Table 16. The HDPE geomembrane should be placed on the exterior of the concrete vault and sandwiched directly between the concrete and GCL to the extent practicable. Table 17 provides reasoning as to why the HDPE geomembrane should be located exterior to the concrete vault rather than internal. This arrangement allows the vault concrete to provide radiation shielding for the geomembrane, improves diffusional properties by having the concrete and geomembrane in intimate direct contact, improves the hydraulic properties by allowing the GCL to hydraulically plug any holes created by tensile stress cracking of the geomembrane, and maintains a diffusion rather than advection driven contaminant transport system by having the components back up one another. Other recommended design requirements are provided in Table 16.
- Shielding the HDPE geomembrane with 4 to 10-inches of concrete should ensure that the total dose to the HDPE geomembrane is less than 2.6 Mrad over 10,000 years. It is recommended that dose calculations be performed to verify the total dose to the geomembrane is less than 2.6 Mrad over 10,000 years, once Vault #2 conceptual design has been completed.
- It is recommended that the Table 16 placement requirements be considered.
- Since oxygen is probably the greatest contributor to HDPE geomembrane degradation, it is recommended that methods to minimize its presence over the period of concern be considered. The use of reducing materials such as blast furnace slag and granular iron within layers adjacent to the HDPE could be utilized to scavenge oxygen.

Table 16. Recommended HDPE Geomembrane Requirements

Type of Requirements	Requirement
Material	High Density Polyethylene (HPDE)
	100 mil thickness
	Smooth (not textured)
	Conform to Geosynthetic Research Institute (GRI) Standard Specification GM13 rev. 6 (6/23/03) for "Test Properties, Testing Frequency and Recommended Warranty for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes" (GRI 2003). Particularly conform to requirements of Table 1(a) – High Density Polyethylene (HDPE) Geomembrane – Smooth. This standard can be found at www.geosynthetic-institute.org/specs.htm
Design	HDPE geomembrane and geosynthetic clay liner (GCL) to fully encase the outside bottom and sides of the concrete vault (a future HDPE geomembrane will be placed on the vault top as part of final closure)
	The HDPE geomembrane on the sides of the concrete vault should accommodate future placement of a HDPE geomembrane on the vault top at final closure
	Intimate direct contact of HDPE geomembrane with concrete vault, where possible (this improves the diffusional properties of the vault)
	Intimate direct contact with GCL in all cases: - For HDPE geomembrane located below vault base, GCL to be located immediately below the HDPE - For HDPE geomembrane located on the vault sides and on the sides and top surface of vault base, GCL to be located immediately on the outside of the HDPE
	Minimize tensile stress within the HDPE geomembrane
	Minimize abrupt sharp changes in HDPE geomembrane direction. This is of particular concern at the transition from beneath the vault base to the vault sides. (abrupt sharp changes in HDPE direction induce stresses which can be later locations of stress cracking)
	HDPE geomembrane should only be in direct contact with concrete, GCL, geotextile, or soil (soil should be free of gravel sized material (gravel ≥ No. 4 sieve) or greater and any other deleterious materials)

Table 16. Recommended HDPE Geomembrane Requirements (continued)

Type of Requirements	Requirement
Placement	HDPE geomembrane installation shall be conducted in a manner that avoids damaging it.
	Wrinkle-free HDPE geomembrane installation (wrinkles in HDPE induce stresses which can be later locations of stress cracking)
	Minimize HDPE geomembrane exposure to UV radiation (i.e. sunlight)
	Minimize length of seaming required (A typical 100-mil HDPE geomembrane comes in 22 to 23 foot widths and 300 to 400 foot lengths. In order to minimize seams on the side of the concrete vault, a vertical mandrel could be used to wrap the HDPE geomembrane lengthwise around the vault sides. This would result in the requirement for only two vertical seams in the HDPE geomembrane on the vault sides. Similar use of a mandrel for an HDPE application has previously been performed at SRS.)
	Seams shall be made using either hot wedge or extrusion seaming, as appropriate.
	HDPE geomembrane QA/QC shall be implemented during installation to primarily perform the following: - Verify that placement is conducted per the specifications. - Detect holes in and damage to the geomembrane and make repairs as necessary. - Verify that seaming is conducted properly and make repairs as necessary. - Verify that materials placed immediately adjacent to the HDPE geomembrane are appropriately placed so that they will not damage it. Particular emphases shall be placed on any placement of poured in place concrete or controlled compacted soil on top of an HDPE geomembrane.

Table 17. HDPE Location Evaluation (i.e. External or Internal to Concrete Vault)

Parameter	External HDPE	Internal HDPE
Maintenance of the total absorbed dose to less than 2.6 Mrad is preferable	8 inches of concrete between the HDPE and Saltstone would reduce the absorbed dose by an estimated factor of 21; thus increasing the longevity of the HDPE from a radiation standpoint.	HDPE on the inside of the vault would be in direct contact with Saltstone and receive the maximum absorbed dose.
Minimization of contact with Saltstone leachate is preferable	Direct contact with Saltstone leachate would not occur	The HDPE would be in direct contact with the Saltstone leachate
Minimization of contact with oxygen is preferable	HDPE contact with oxygen would be limited by the GCL and concrete surrounding it. Both should be near saturation, which will limit the oxygen availability.	HDPE contact with oxygen would be limited by the concrete and Saltstone surrounding it. Both should be near saturation and the Saltstone is reducing, which will greatly limit the oxygen availability.
Temperature minimization is preferable	Very little difference in temperature would exist between the inside and the outside of the eight inch concrete, so temperature isn't really a consideration.	Very little difference in temperature would exist between the inside and the outside of the eight inch concrete, so temperature isn't really a consideration.
Tensile Stress minimization is preferable	No significant tensile stress anticipated except at the transition from beneath the base to the sides. At this location consideration should be given to providing smooth rather than abrupt changes in the HDPE direction.	No significant tensile stress anticipated in the HDPE on top of the base. However significant tensile stresses could form in the HDPE on the sides after the Saltstone shrinks away. This could cause the HDPE to slump and form creases where tensile stresses could concentrate and promote the formation of cracks.
Intimate contact of HDPE with concrete sides of the vault (~10,000 ft^2) is preferable	Soil pressure from backfill around vault would ensure intimate contact of the HDPE with the concrete sides.	Shrinkage of Saltstone could result in formation of a gap between the HDPE and concrete walls, since there would be no applied pressure to keep the HDPE in contact with the walls.

Table 17. HDPE Location Evaluation (i.e. External or Internal to Concrete Vault) (continued)

Parameter	External HDPE	Internal HDPE
Intimate contact of HDPE with concrete base of the vault (~19,000 ft^2) is preferable	In order for the HDPE to be in intimate contact with the concrete, the poured in place concrete base would have to be placed directly on top of the HDPE. This could subject the HDPE to the potential for significant construction damage. To protect the HDPE from construction damage, a compacted soil layer might be placed on top of the HDPE, between it and the concrete. This would mean that the HDPE and concrete were not in direct contact.	The Saltstone poured on top of the HDPE and concrete base would ensure intimate contact of the HDPE with the concrete base.
Diffusion Barrier	Conceptually this configuration is not as preferable. However intimate contact with the concrete would be maintained and diffusion out would be limited to the locations where holes have formed in the HDPE.	Conceptually this configuration is preferable. However the HPDE has to be maintained in intimate contact with the concrete, which might be difficult for this configuration on the sides.

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9 APPENDICES

Appendix A, Average Yearly and Cumulative Average Temperatures
Appendix B, Antioxidant Time of Depletion Calculation
Appendix C, Total Dose to HDPE Geomembrane Calculation
Appendix D, Nitrate Groundwater Concentration Calculation

Appendix A, Average Yearly and Cumulative Average Temperatures

Elapsed Time (years)	Average Yearly Temperature Adjacent to Saltstone (^{o}C)	Cumulative Average Temperature Adjacent to Saltstone (^{o}C)	Average Yearly Temperature 1-ft Away from Saltstone (^{o}C)	Cumulative Average Temperature 1-ft Away from Saltstone (^{o}C)
1	64.36	64.36	61.88	61.88
2	63.22	63.79	62.44	62.16
3	57.43	61.67	57.05	60.46
4	52.78	59.45	52.55	58.48
5	49.48	57.45	49.31	56.65
6	47.12	55.73	46.98	55.04
7	45.37	54.25	45.25	53.64
8	44.05	52.98	43.94	52.43
9	43.01	51.87	42.91	51.37
10	42.17	50.90	42.08	50.44
11	41.49	50.04	41.39	49.62
12	40.91	49.28	40.82	48.88
13	40.41	48.60	40.33	48.23
14	39.98	47.98	39.90	47.63
15	39.60	47.43	39.52	47.09
16	39.25	46.91	39.17	46.59
17	38.93	46.45	38.86	46.14
18	38.64	46.01	38.57	45.72
19	38.37	45.61	38.30	45.33
20	38.12	45.24	38.05	44.97
21	37.88	44.89	37.82	44.62
22	37.66	44.56	37.59	44.31
23	37.44	44.25	37.38	44.00
24	37.24	43.96	37.18	43.72
25	37.04	43.68	36.98	43.45
26	36.85	43.42	36.80	43.19
27	36.67	43.17	36.61	42.95
28	36.49	42.93	36.44	42.72
29	36.32	42.70	36.27	42.50
30	36.16	42.48	36.10	42.28
31	35.99	42.27	35.94	42.08
32	35.84	42.07	35.79	41.88
33	35.68	41.88	35.63	41.69
34	35.53	41.69	35.49	41.51
35	35.39	41.51	35.34	41.33
36	35.24	41.34	35.20	41.16
37	35.10	41.17	35.06	41.00
38	34.97	41.01	34.92	40.84
39	34.83	40.85	34.79	40.68
40	34.70	40.69	34.66	40.53
41	34.57	40.54	34.53	40.39

Elapsed Time (years)	Average Yearly Temperature Adjacent to Saltstone (°C)	Cumulative Average Temperature Adjacent to Saltstone (°C)	Average Yearly Temperature 1-ft Away from Saltstone (°C)	Cumulative Average Temperature 1-ft Away from Saltstone (°C)
42	34.45	40.40	34.40	40.24
43	34.32	40.26	34.28	40.11
44	34.20	40.12	34.16	39.97
45	34.08	39.99	34.04	39.84
46	33.96	39.85	33.93	39.71
47	33.85	39.73	33.81	39.58
48	33.74	39.60	33.70	39.46
49	33.63	39.48	33.59	39.34
50	33.52	39.36	33.48	39.22
51	33.41	39.24	33.38	39.11
52	33.31	39.13	33.27	39.00
53	33.21	39.02	33.17	38.89
54	33.11	38.91	33.07	38.78
55	33.01	38.80	32.97	38.67
56	32.91	38.70	32.88	38.57
57	32.82	38.59	32.78	38.47
58	32.72	38.49	32.69	38.37
59	32.63	38.39	32.60	38.27
60	32.54	38.30	32.51	38.18
61	32.45	38.20	32.42	38.08
62	32.37	38.11	32.33	37.99
63	32.28	38.01	32.25	37.90
64	32.20	37.92	32.16	37.81
65	32.12	37.83	32.08	37.72
66	32.04	37.74	32.00	37.63
67	31.96	37.66	31.92	37.55
68	31.88	37.57	31.85	37.46
69	31.80	37.49	31.77	37.38
70	31.73	37.41	31.70	37.30
71	31.66	37.33	31.62	37.22
72	31.59	37.25	31.55	37.14
73	31.52	37.17	31.48	37.06
74	31.45	37.09	31.41	36.99
75	31.38	37.02	31.35	36.91
76	31.31	36.94	31.28	36.84
77	31.25	36.87	31.22	36.77
78	31.19	36.79	31.15	36.69
79	31.12	36.72	31.09	36.62
80	31.06	36.65	31.03	36.55
81	31.00	36.58	30.97	36.48
82	30.94	36.51	30.91	36.42
83	30.89	36.44	30.85	36.35
84	30.83	36.38	30.80	36.28

Elapsed Time (years)	Average Yearly Temperature Adjacent to Saltstone (^{o}C)	Cumulative Average Temperature Adjacent to Saltstone (^{o}C)	Average Yearly Temperature 1-ft Away from Saltstone (^{o}C)	Cumulative Average Temperature 1-ft Away from Saltstone (^{o}C)
85	30.78	36.31	30.74	36.22
86	30.72	36.25	30.69	36.15
87	30.67	36.18	30.64	36.09
88	30.62	36.12	30.58	36.03
89	30.57	36.06	30.53	35.97
90	30.52	36.00	30.48	35.90
91	30.47	35.93	30.43	35.84
92	30.42	35.87	30.39	35.79
93	30.37	35.82	30.34	35.73
94	30.33	35.76	30.29	35.67
95	30.28	35.70	30.25	35.61
96	30.24	35.64	30.20	35.56
97	30.20	35.59	30.16	35.50
98	30.15	35.53	30.12	35.44
99	30.11	35.48	30.08	35.39
100	30.07	35.42	30.04	35.34
101	30.03	35.37	30.00	35.28
102	29.99	35.32	29.96	35.23
103	29.96	35.26	29.92	35.18
104	29.92	35.21	29.88	35.13
105	29.88	35.16	29.85	35.08
106	29.85	35.11	29.81	35.03
107	29.81	35.06	29.78	34.98
108	29.78	35.01	29.74	34.93
109	29.74	34.97	29.71	34.88
110	29.71	34.92	29.68	34.84
111	29.68	34.87	29.64	34.79
112	29.65	34.82	29.61	34.74
113	29.62	34.78	29.58	34.70
114	29.59	34.73	29.55	34.65
115	29.56	34.69	29.52	34.61
116	29.53	34.64	29.49	34.56
117	29.50	34.60	29.47	34.52
118	29.47	34.56	29.44	34.48
119	29.45	34.51	29.41	34.44
120	29.42	34.47	29.38	34.39
121	29.39	34.43	29.36	34.35
122	29.37	34.39	29.33	34.31
123	29.34	34.35	29.31	34.27
124	29.32	34.30	29.28	34.23
125	29.30	34.26	29.26	34.19
126	29.27	34.23	29.24	34.15

Elapsed Time (years)	Average Yearly Temperature Adjacent to Saltstone (^oC)	Cumulative Average Temperature Adjacent to Saltstone (^oC)	Average Yearly Temperature 1-ft Away from Saltstone (^oC)	Cumulative Average Temperature 1-ft Away from Saltstone (^oC)
127	29.25	34.19	29.22	34.11
128	29.23	34.15	29.19	34.07
129	29.21	34.11	29.17	34.04
130	29.19	34.07	29.15	34.00
131	29.16	34.03	29.13	33.96
132	29.14	34.00	29.11	33.92
133	29.12	33.96	29.09	33.89
134	29.11	33.92	29.07	33.85
135	29.09	33.89	29.05	33.82
136	29.07	33.85	29.03	33.78
137	29.05	33.82	29.01	33.75
138	29.03	33.78	29.00	33.71
139	29.01	33.75	28.98	33.68
140	29.00	33.71	28.96	33.64
141	28.98	33.68	28.94	33.61
142	28.96	33.65	28.93	33.58
143	28.95	33.61	28.91	33.54
144	28.93	33.58	28.90	33.51
145	28.92	33.55	28.88	33.48
146	28.90	33.52	28.87	33.45
147	28.89	33.49	28.85	33.42
148	28.87	33.46	28.84	33.39
149	28.86	33.42	28.82	33.36
150	28.85	33.39	28.81	33.33
151	28.83	33.36	28.80	33.30
152	28.82	33.33	28.78	33.27
153	28.81	33.30	28.77	33.24
154	28.79	33.28	28.76	33.21
155	28.78	33.25	28.75	33.18
156	28.77	33.22	28.73	33.15
157	28.76	33.19	28.72	33.12
158	28.75	33.16	28.71	33.09
159	28.74	33.13	28.70	33.07
160	28.73	33.11	28.69	33.04
161	28.72	33.08	28.68	33.01
162	28.70	33.05	28.67	32.99
163	28.69	33.02	28.66	32.96
164	28.68	33.00	28.65	32.93
165	28.67	32.97	28.64	32.91
166	28.67	32.95	28.63	32.88
167	28.66	32.92	28.62	32.86
168	28.65	32.89	28.61	32.83

Elapsed Time (years)	Average Yearly Temperature Adjacent to Saltstone (°C)	Cumulative Average Temperature Adjacent to Saltstone (°C)	Average Yearly Temperature 1-ft Away from Saltstone (°C)	Cumulative Average Temperature 1-ft Away from Saltstone (°C)
169	28.64	32.87	28.60	32.80
170	28.63	32.84	28.59	32.78
171	28.62	32.82	28.58	32.76
172	28.61	32.80	28.58	32.73
173	28.60	32.77	28.57	32.71
174	28.60	32.75	28.56	32.68
175	28.59	32.72	28.55	32.66
176	28.58	32.70	28.54	32.64
177	28.57	32.68	28.54	32.61
178	28.57	32.65	28.53	32.59
179	28.56	32.63	28.52	32.57
180	28.55	32.61	28.52	32.55
181	28.55	32.59	28.51	32.52
182	28.54	32.56	28.50	32.50
183	28.53	32.54	28.50	32.48
184	28.53	32.52	28.49	32.46
185	28.52	32.50	28.48	32.44
186	28.51	32.48	28.48	32.41
187	28.51	32.46	28.47	32.39
188	28.50	32.43	28.47	32.37
189	28.50	32.41	28.46	32.35
190	28.49	32.39	28.45	32.33
191	28.49	32.37	28.45	32.31
192	28.48	32.35	28.44	32.29
193	28.48	32.33	28.44	32.27
194	28.47	32.31	28.43	32.25
195	28.47	32.29	28.43	32.23
196	28.46	32.27	28.42	32.21
197	28.46	32.25	28.42	32.19
198	28.45	32.23	28.41	32.17
199	28.45	32.22	28.41	32.15

Appendix B, Antioxidant Time of Depletion Calculation

Antioxidant time of depletion for HDPE in Saltstone service has been estimated utilizing the methodology of Mueller and Jakob (2003). They utilized the van't Hoff rule for the temperature dependence of antioxidant depletion time and their measured antioxidant depletion time of 5 years for HDPE geomembranes immersed in 80°C de-ionized water.

van't Hoff rule:

$$t_1(T) = t_1(T')\, e^{\frac{E_a}{R}\left[\frac{1}{T}-\frac{1}{T'}\right]},$$

where $t_1(T)$ = antioxidant depletion period in years at the ambient temperature of the HDPE; $t_1(T')$ = antioxidant depletion period in years at test temperature of 80°C (i.e. 5 years); E_a = depletion process activation energy; R = universal gas constant (8.319 J/mol K); T = ambient temperature of the HDPE in K (K = 273.15 + °C); T' = test temperature in K = 273.15 + 80°C = 353.15

van't Hoff rule with substitution of 5 year time of depletion in 80°C de-ionized water:

$$t_1(T) = 5\ yrs\ e^{\frac{E_a}{8.319\ J/mol\ K}\left[\frac{1}{T}-\frac{1}{353.15\ K}\right]},$$

where $t_1(T)$ = antioxidant depletion period in years at the ambient temperature of the HDPE; E_a = depletion process activation energy; T = ambient temperature of the HDPE in K (K = 273.15 + °C)

As outlined in Section 5.4.1, Needham et al. (2004) concluded that, "Values of activation energy of 60-75 kJ/mol appear a reasonable, conservative estimate." Therefore for determination of a conservative antioxidant time of depletion for a HDPE geomembrane in Saltstone service, an activation energy of 60 kJ/mol will be utilized. This results in the following equation:

$$t_1(T) = 5\ yrs\ e^{\frac{60{,}000\ J/mol}{8.319\ J/mol\ K}\left[\frac{1}{T}-\frac{1}{353.15\ K}\right]},$$

where $t_1(T)$ = antioxidant depletion period in years at the ambient temperature of the HDPE; T = ambient temperature of the HDPE in K (K = 273.15 + °C)

The antioxidant depletion time at various ambient temperatures has been determined below and compared to the cumulative average temperature from Appendix A that most closely corresponds to the calculated antioxidant depletion time (i.e. antioxidant depletion time ≈ elapsed time from Appendix A). The year where the temperature used to calculate the antioxidant depletion time most closely approximates the cumulative average temperature from Appendix A is the appropriate antioxidant depletion time for HDPE in Saltstone service. As seen in the calculations below the antioxidant depletion time is estimated to occur some time between year 92 and 99. Therefore it has been determined that a HDPE geomembrane in Saltstone service would have a conservative antioxidant depletion time of at least 90 years.

Temperature (°C)	Temperature [1] (K)	Exponent [2]	Antioxidant Depletion Time [3] (years)	Cumulative Average Temperature from Appendix A (°C)	Elapsed Time from Appendix A (years)
30	303.15	3.37	145.2	33.48-33.55	145
31	304.15	3.29	134.2	33.85-33.92	134
32	305.15	3.21	124.2	34.23-34.30	124
33	306.15	3.14	115.0	34.61-34.69	115
34	307.15	3.06	106.5	34.98-35.06	107
35	308.15	2.98	98.7	35.39-35.48	99
36	309.15	2.91	91.5	35.79-35.87	92
37	310.15	2.83	84.9	36.22-36.31	85
38	311.15	2.76	78.7	36.62-36.72	79
39	312.15	2.68	73.1	37.06-37.17	73
40	313.15	2.61	67.9	37.46-37.57	68
41	314.15	2.54	63.1	37.90-38.01	63
42	315.15	2.46	58.7	38.27-38.39	59
43	316.15	2.39	54.6	38.67-38.80	55
44	317.15	2.32	50.8	39.11-39.24	51
45	318.15	2.25	47.3	39.58-39.73	47
46	319.15	2.18	44.0	39.31-40.12	44
47	320.15	2.11	41.0	40.39-40.54	41
48	321.15	2.03	38.3	40.84-41.01	38
49	322.15	1.97	35.7	41.16-41.34	36
50	323.15	1.90	33.3	41.69-41.88	33
55	328.15	1.56	23.7	43.72-43.96	24
60	333.15	1.23	17.0	46.14-46.45	17

[1] K = 273.15 + °C

[2] Exponent = $\frac{60{,}000\ J/mol}{8.319\ J/mol\ K}\left[\frac{1}{T}-\frac{1}{353.15\ K}\right]$

[3] Antioxidant Depletion Time = $5\ yrs\ e^{Exponent}$

Appendix C, Total Dose to HDPE Geomembrane Calculation

The time until a total dose of 2.6 Mrad (see Section 5.5) is reached assuming no radioactive decay is calculated below:

Concrete Thickness (inches)	Table 2 Dose Rate at Time Zero for Saltstone made from 0.2 Ci/gal Cs-137 Salt Solution [1] (rad/hr)	Time until 2.6 Mrad Reached - No Radioactive Decay Considered [2] (years)
0	1.10E+01	27.0
2	6.23E+00	47.6
4	2.73E+00	108.8
6	1.19E+00	248.5
8	5.22E-01	567.8
10	1.62E-01	1,833.7
12	1.13E-01	2,619.4
14	5.75E-02	5,161.7
16	3.64E-02	8,140.0

[1] Values taken from Section 3.5 Table 2

[2] Time until 2.6 Mrad Reached = (2,600,000 / Table 2 Dose Rate at Time Zero) / 8765.81 hrs/yr

The time until a total dose of 2.6 Mrad (see Section 5.5) is reached assuming no concrete and all activity is due to Cs-137 and calculating radioactive decay based upon Cs-137's 30.07 year half-life is calculated below:

Year	Dose Rate for Saltstone made from 0.2 Ci/gal Cs-137 Salt Solution with 0 inch thick Concrete [1] (rad/hr)	Average Dose Rate over 10 year period [2] (rad/hr)	Total Dose over 10 year period [3] (rad)	Cumulative Dose [4] (rad)
0	11.00	0	0	0
10	8.737728601	9.870328586	865,214.25	865,214.25
20	6.93887092	7.838299761	687,090.46	1,552,304.71
30	5.510348495	6.224609708	545,637.46	2,097,942.17
40	4.375919496	4.943133996	433,305.73	2,531,247.91
50	3.475038185	3.925478841	344,100.02	2,875,347.93

[1] The dose rate at year 0 was taken from Section 3.5 Table 2. The dose rate at subsequent years was obtained as follows: $Dose\ rate = 11\ rad / yr\ e^{-\left(\frac{Year \times Ln(2)}{30.07\ yrs}\right)}$

[2] $Average\ dose\ rate\ over\ 10\ years = \frac{(previous\ dose\ rate + current\ dose\ rate)}{2}$

[3] $Total\ dose\ over\ 10\ years = Average\ dose\ rate\ over\ 10\ years \times 87{,}658.1\ hrs/10\ yrs$

[4] $Cumulative\ dose = previous\ cumulative\ dose + current\ total\ dose\ over\ 10\ years$

The time until a total dose of 2.6 Mrad (see Section 5.5) is reached assuming 2 inches of concrete and all activity is due to Cs-137 and calculating radioactive decay based upon Cs-137's 30.07 year half-life is calculated below:

Year	Dose Rate for Saltstone made from 0.2 Ci/gal Cs-137 Salt Solution with 2 inch thick Concrete [1] (rad/hr)	Average Dose Rate over 50 year period [2] (rad/hr)	Total Dose over 50 year period [3] (rad)	Cumulative Dose [4] (rad)
0	6.23	0	0	0
50	1.967309	4.098176	1,796,191.60	1,796,191.60
100	0.621332	1.294321	567,288.46	2,363,480.06
150	0.196234	0.408783	179,165.85	2,542,645.91
200	0.061976	0.129105	56,585.68	2,599,231.59
250	0.019574	0.040775	17,871.37	2,617,102.96

[1] The dose rate at year 0 was taken from Section 3.5 Table 2. The dose rate at subsequent years was obtained as follow: $Dose\ rate = 6.23\ rad/yr\ e^{-\left(\frac{Year \times Ln(2)}{30.07\ yrs}\right)}$

[2] $Average\ dose\ rate\ over\ 50\ years = \frac{(previous\ dose\ rate + current\ dose\ rate)}{2}$

[3] $Total\ dose\ over\ 50\ years = Average\ dose\ rate\ over\ 50\ years \times 438{,}290.5\ hrs/50\ yrs$

[4] $Cumulative\ dose = previous\ cumulative\ dose + current\ total\ dose\ over\ 50\ years$

The time until a total dose of 2.6 Mrad (see Section 5.5) is reached assuming 4 inches of concrete and all activity is due to Cs-137 and calculating radioactive decay based upon Cs-137's 30.07 year half-life is calculated below:

Year	Dose Rate for Saltstone made from 0.2 Ci/gal Cs-137 Salt Solution with 4 inch thick Concrete [1] (rad/hr)	Average Dose Rate over 50 year period [2] (rad/hr)	Total Dose over 50 year period [3] (rad)	Cumulative Dose [4] (rad)
0	2.73	0	0	0
50	0.86111	1.79381	786,209.99	786,209.99
100	0.271963	0.566536	248,307.51	1,034,517.50
150	0.085894	0.178928	78,422.58	1,112,940.08
200	0.027128	0.056511	24,768.08	1,137,708.17
250	0.008568	0.017848	7,822.47	1,145,530.63
300	0.002706	0.005637	2,470.56	1,148,001.19
350	0.000855	0.00178	780.27	1,148,781.46
400	0.00027	0.000562	246.43	1,149,027.89
450	8.52E-05	0.000178	77.83	1,149,105.72
500	2.69E-05	5.61E-05	24.58	1,149,130.31
550	8.5E-06	1.77E-05	7.76	1,149,138.07
600	2.69E-06	5.59E-06	2.45	1,149,140.52
650	8.48E-07	1.77E-06	0.77	1,149,141.30
700	2.68E-07	5.58E-07	0.24	1,149,141.54
750	8.46E-08	1.76E-07	0.08	1,149,141.62
800	2.67E-08	5.57E-08	0.02	1,149,141.64
850	8.44E-09	1.76E-08	0.01	1,149,141.65
900	2.67E-09	5.55E-09	0.00	1,149,141.65
950	8.42E-10	1.75E-09	0.00	1,149,141.65
1000	2.66E-10	5.54E-10	0.00	1,149,141.65

[1] The dose rate at year 0 was taken from Section 3.5 Table 2. The dose rate at subsequent years was obtained as follow: $Dose\ rate = 2.73\ rad / yr\ e^{-\left(\frac{Year \times Ln(2)}{30.07\ yrs}\right)}$

[2] $Average\ dose\ rate\ over\ 50\ years = \frac{(previous\ dose\ rate + current\ dose\ rate)}{2}$

[3] $Total\ dose\ over\ 50\ years = Average\ dose\ rate\ over\ 50\ years \times 438{,}290.5\ hrs / 50\ yrs$

[4] $Cumulative\ dose = previous\ cumulative\ dose + current\ total\ dose\ over\ 50\ years$ (The cumulative dose remains at 1,149,141.65 rads from year 850 to 10,000, since the calculation was based upon radioactive decay of Cs-137 with a half-life of 30.07 years. 850 years represents approximately 28 half-lives, which mean that based upon Cs-137 essentially not radioactivity remains after 850 years.)

Calculations for additional thicknesses of concrete are not required, since increases the thickness would only mean that within 10,000 years the total dose to the HDPE geomembrane would be much less than that for the 2-inch thick concrete above.

Appendix D, Nitrate Groundwater Concentration Calculation

D-1 METHODOLOGY

The nitrate groundwater concentrations have been estimated at years 100, 1,000, and 10,000 for the Vault #2 Cylindrical Vault with and without a 100-mil HDPE geomembrane per the methodology outlined below. The estimates do not take into account potential cracking of the vault concrete.

- Vault #2 has been analyzed as a 154-foot inside diameter, minimum 20-foot high cylinder made out of concrete a minimum 8-inch thick and 100-mil HDPE covered with a closure cap consistent with that outlined within Phifer and Nelson (2003).
- HDPE degradation has been analyzed over time consistent with the “fair” case degradation outlined by Needham et al. (2004).
- Vault concrete and Saltstone degradation has been analyzed over time as outlined by Cook (2004).
- The HELP model (USEPA 1994a and USEPA 1994b) has been used to estimate the flux of water through and around the Cylindrical Vault.
- The water flux out the bottom of the Cylindrical Vault has been analyzed assuming that the nitrate concentrations are equal to that of the Saltstone pore fluid (i.e. 47,234 mg/L nitrate/nitrite as nitrogen (WSRC 2002)). Diffusion has not been considered out the bottom.
- The water flux around the Cylindrical Vault has been analyzed assuming it contains nitrate due to diffusion out the side of the vault. Advection has not been considered out the sides.
- The nitrate concentration has been analyzed for a monitoring well with a screen length of 10 feet and compared to the nitrate maximum contaminant level of 10 mg/L of nitrate as nitrogen. The nitrate concentration within the 10-foot screen interval has been estimated by determining the mass of nitrate that enters a 20-foot by 2500-foot area (50,000 ft^2) per a given time period divided by the volume of water that enters the area over the same given time period. It is assumed that this 50,000 ft^2 feeds the 10-foot screen interval.

D-2 ASSUMPTIONS

The following are the major assumptions associated with these nitrate groundwater estimations:

- It is assumed that Vault #2 is a 154-foot inside diameter, minimum 20-foot high cylinder made out of concrete a minimum 8-inch thick and 100-mil HDPE. It is also assumed that the vault will be covered with a closure cap consistent with that outlined within Phifer and Nelson (2003).
- It is assumed that the HDPE will degrade over time consistent with the “fair” case degradation outlined by Needham et al. (2004). HDPE degradation results in holes in the HDPE, while the intact portion of the HDPE is assumed to maintain it initial effective hydraulic conductivity of 2.0E-13 cm/s (USEPA 1994a; USEPA 1994b).
- It is assumed that there is a linear relationship between the area of holes for the points immediately around years 100, 1,000, and 10,000, respectively.
- It is assumed that the vault concrete and Saltstone will degrade over time as outlined by Cook (2004). Cook (2004) assumes that the saturated hydraulic conductivity increases over time, while the porosity and effective diffusion coefficient are assumed to remain constant over time.

- It is assumed that the HELP model (USEPA 1994a and USEPA 1994b) can be used to adequately estimate the flux of water through and around the Cylindrical Vault.
- It is assumed that surface run-on from one area to another in the HELP modeling can be ignored since it is a small amount and ignoring it is conservative.
- It is assumed that the drain for the drainage layer above the vault roof effectively removes all water from the drainage layer. This is a conservative assumption since it ignores potential dilution water.
- It is assumed that the water flux out the bottom of the Cylindrical Vault contains nitrate concentrations equal to that of the Saltstone pore fluid (i.e. 47,234 mg/L nitrate/nitrite as nitrogen (WSRC 2002)). Diffusion is not considered out the bottom.
- It is assumed that the water flux around the Cylindrical Vault contains nitrate due to diffusion out the side of the vault. Advection is not considered out the sides. The following assumptions have been made to estimate the nitrate diffusion flux out the side of the vault:
    - It is assumed that Fick's First Law can adequately represent nitrate diffusion through the diffusion barriers,
    - Nitrate concentrations of the Saltstone pore water remains constant at 47,234 mg/L nitrate/nitrite as nitrogen (i.e. constant over time) (WSRC 2002),
    - Steady-state conditions,
    - No advection through the walls,
    - Nitrate is conservative (i.e. non-reactive species with a $K_d = 0$) (WSRC 1992),
    - It is assumed that nitrate does not diffuse through intact portions of the HDPE geomembrane and that any diffusion through the HDPE only occur at holes in the HDPE,
    - Saturated conditions, and
    - Flushing boundary condition (i.e. nitrate concentration of 0 at the boundary due to water flux which transports all nitrate away).
- It is assumed that diffusion out the top of the vault is insignificant and can be ignored.
- It is assumed that a typical monitoring well has a screen length of 10 feet. It is further assumed that it is regulatorily satisfactory if the average nitrate concentration over a 10-foot screen interval is less than 10 mg/L of nitrate as nitrogen, that the 10-foot screen interval represents a 2500-foot infiltration interval on the ground surface parallel to the direction of groundwater flow, and that the well has a ten-foot radius of influence (i.e. the monitoring well intercepts a 20-foot wide area perpendicular to the groundwater flow direction). This means that the mass of nitrate that enters the 20-foot by 2500-foot area (50,000 ft^2) per a given time period divided by the volume of water that enters the area over the same given time period equals the nitrate concentration of the 10-foot screen interval. (WSRC 2002)
- It is assumed that the closure cap has a 3% slope over a 450-foot slope length and that it entirely covers the 2500-foot footprint that feeds into the 10-foot screen interval.

D-3 CONSERVATISM

The following are the primary areas of conservatism associated with these nitrate groundwater estimations:

- The steady state assumption that the nitrate mass flux from the entire wall height and bottom remains constant over time so that the mass from all locations arrives at the monitoring well at the same time is a conservative assumption since the nitrate transport will in actuality be transient rather than steady state.

- The assumption that Saltstone nitrate concentrations in the pore water immediately adjacent to the vault concrete remain constant over time at 47,234 mg/L nitrate/nitrite as nitrogen is a conservative assumption, since over time this concentration will be depleted over time starting at the edges of the Saltstone and working inward and the Saltstone itself will therefore become an increasing barrier to diffusion over time.
- The assumption that nitrate is conservative (i.e. is not bound to soil and does not degrade) is a conservative assumption since nitrate can be biologically degraded.
- The assumption of flushing boundary conditions (i.e. nitrate concentration of 0 at the boundary due to water flux which transports all nitrate away) is a conservative assumption since it maximizes the calculated diffusion flux and is not likely to occur.
- The assumption that the water flux out the bottom of the Cylindrical Vault contains nitrate concentrations equal to that of the Saltstone pore fluid (i.e. 47,234 mg/L nitrate/nitrite as nitrogen (WSRC 2002)) throughout time is a conservative assumption, since this concentration will be depleted over time starting at the edges of the Saltstone and working inward.
- The assumption that the closure cap entirely covers the 2500-foot footprint that feeds into the 10-foot screen interval is conservative at least for the first 1000 years, since this assumption limits the volume of water mixed with the nitrate mass and results in a higher estimated concentration during the first 1000 years, since it is not likely that the closure cap will cover the entire 2500-foot footprint.
- The planned use of a geosynthetic clay liner (GCL) in immediate contact with the HDPE geomembrane is not taken into account.

D-4 CALCULATIONS

D-4.1 VAULT #2 AND CLOSURE CAP CONFIGURATION

It is assumed that Vault #2 is a 154-foot inside diameter, minimum 20-foot high cylinder made out of concrete a minimum 8-inch thick and 100-mil HDPE. It is also assumed that the vault will be covered with a closure cap consistent with that outlined within Phifer and Nelson (2003). The closure cap and Vault #2 configurations are provided below.

Closure Cap (Phifer and Nelson 2003) and Vault #2 Cylindrical Vault Configuration:

Layer	Thickness (inches)
Topsoil	6
Upper Backfill	30
Erosion Barrier	12
Middle Backfill	12
Geotextile Filter Fabric	-
Upper Drainage Layer	12
Upper GCL	0.2
Lower Backfill	58.57
Geotextile Filter Fabric	-
Lower Drainage Layer	24
Roof HDPE	0.1
Concrete Vault Roof	8
Saltstone	240
Floor HDPE	0.1
Concrete Vault Floor	24

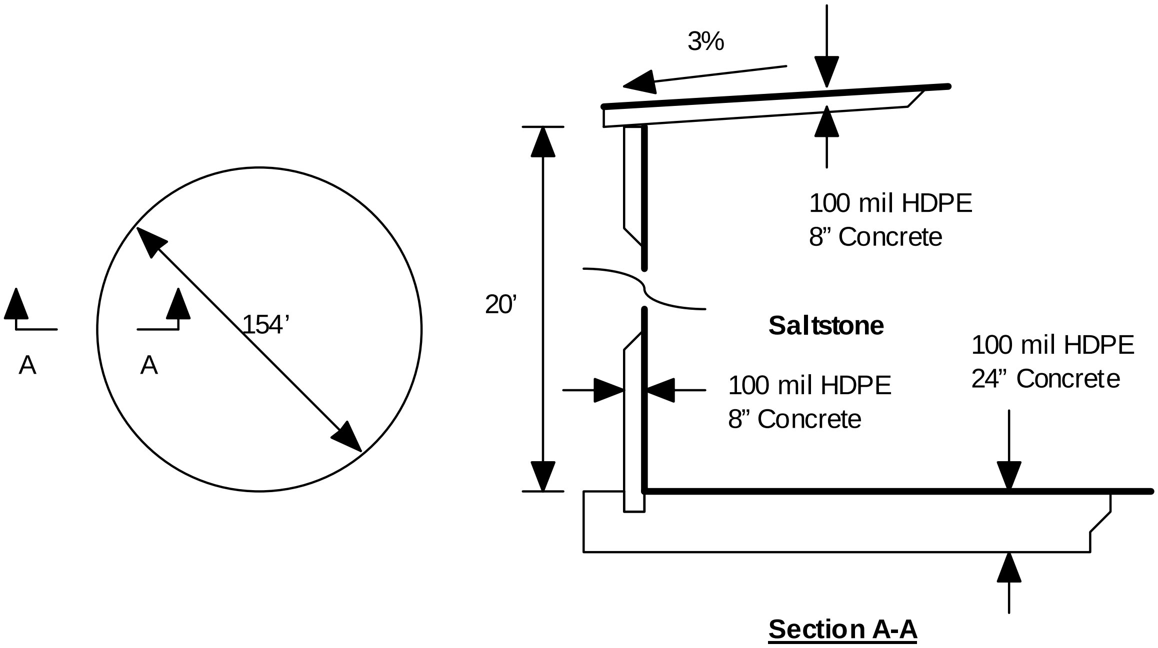

Figure D-1. Vault #2 Cylindrical Vault

D-4.2 HDPE DEGRADATION

It is assumed that the HDPE will degrade over time consistent with the "fair" case degradation outlined by Needham et al. (2004). HDPE degradation results in holes in the HDPE, while the intact portion of the HDPE is assumed to maintain it initial effective hydraulic conductivity of 2.0E-13 cm/s (USEPA 1994a; USEPA 1994b).

Estimation of Duration of Different Stages of Defect Generation in Saltstone HDPE geomembrane based upon the Methodology of Needham et al. (2004):

Stage	Duration (years)	Cumulative (years)	Comments - Assumptions
1	0	0	Vault #2 (Silo) Construction
2	2	2	Filling Vault #2 (Silo) with Saltstone
3	8	10	No hole generation during this stage; minimum 10 year period recommended by Needham et al. (2004)
4	80	90	Oxidation estimated to commence 90 years after construction, based upon Appendix B calculations
5	50	140	Period of further stress cracking during oxidation; 50-year period recommended by Needham et al. (2004)
6	9,860	10,000	Continuing deterioration through 10,000 years

Estimation of Hole Type and Size per Stage of Defect Generation in Saltstone HDPE geomembrane based upon the Methodology of Needham et al. (2004):

Hole Type	Individual Hole Size (mm^2)	Stage					
		1 *		2 **		3	
		# of holes	holes size	# of holes	holes size	# of holes	holes size
pinholes	2.5	20	50	0	0	0	0
holes	50	10	500	0	0	0	0
tears	5000	0	0	0	0	0	0
small cracks	10	0	0	0	0	0	0
large cracks	1000	0	0	0	0	0	0
		total	550	total	0	total	0

Hole Type	Individual Hole Size	Stage					
		4		5		6 ***	
		# of holes	holes size	# of holes	holes size	# of holes	holes size
pinholes	2.5	0	0	0	0	20	50
holes	50	0	0	0	0	10	500
tears	5000	0	0	0	0	0	0
small cracks	10	75	750	100	1000	175	1750
large cracks	1000	35	35000	50	50000	85	85000
		total	35750	total	51000	total	87300

The holes size is in mm^2/Hectare

The individual hole size for pinholes, holes, and tears is taken as the midpoint in the range provided by Needham et al. (2004)

The individual hole size for small cracks and large cracks is taken as that recommended by Needham et al. (2004)

The number of holes is the most likely number or average number from Needham et al. (2004) for the "fair" case except where noted below:
* The anticipated cylindrical configuration of Vault #2 and associated construction methodology seem to preclude the generation of tears during construction.
** Due to the anticipated cylindrical configuration and the nature of Saltstone and its placement, no damage to the HDPE is anticipated during Saltstone placement.
*** # of holes and holes size is per 100 years

Estimation of Size of Holes Generated per Stage for the Needham et al. (2004) Fair Case:

Stage	Cumulative (years)	Size of Holes Generated for the Needham et al. (2004) Fair Case (mm^2 / Hectare)
1	0	550
2	2	0
3	10	0
4	90	35,750
5	140	51,000
6	10,000	87,300 / 100 year

This results in the following cumulative area of holes over time in the HDPE (also see Figure D-2):

Stage	Year	Total Stage Hole Size from above Table (mm^2/Hectare)	Total Cumulative Hole Size [1] (mm^2/Hectare)	Fraction of HDPE membrane with Holes [2]	Percentage (%) of HDPE membrane with Holes [3]
1	0	550	550	5.5E-08	0.0000055
2	2	0	550	5.5E-08	0.0000055
3	10	0	550	5.5E-08	0.0000055
4	90	35,750	36300	0.00000363	0.000363
5	140	51,000	87300	0.00000873	0.000873
6	240	87,300 / 100 yr	174600	0.00001746	0.001746
6	340	87,300 / 100 yr	261900	0.00002619	0.002619
6	440	87,300 / 100 yr	349200	0.00003492	0.003492
6	540	87,300 / 100 yr	436500	0.00004365	0.004365
6	640	87,300 / 100 yr	523800	0.00005238	0.005238
6	740	87,300 / 100 yr	611100	0.00006111	0.006111
6	840	87,300 / 100 yr	698400	0.00006984	0.006984
6	940	87,300 / 100 yr	785700	0.00007857	0.007857
6	1040	87,300 / 100 yr	873000	0.0000873	0.00873
6	1140	87,300 / 100 yr	960300	0.00009603	0.009603
6	1240	87,300 / 100 yr	1047600	0.00010476	0.010476
6	1340	87,300 / 100 yr	1134900	0.00011349	0.011349
6	1440	87,300 / 100 yr	1222200	0.00012222	0.012222
6	1540	87,300 / 100 yr	1309500	0.00013095	0.013095
6	1640	87,300 / 100 yr	1396800	0.00013968	0.013968
6	1740	87,300 / 100 yr	1484100	0.00014841	0.014841

Stage	Year	Total Stage Hole Size from above Table (mm^2/Hectare)	Total Cumulative Hole Size [1] (mm^2/Hectare)	Fraction of HDPE membrane with Holes [2]	Percentage (%) of HDPE membrane with Holes [3]
6	1840	87,300 / 100 yr	1571400	0.00015714	0.015714
6	1940	87,300 / 100 yr	1658700	0.00016587	0.016587
6	2040	87,300 / 100 yr	1746000	0.0001746	0.01746
6	2140	87,300 / 100 yr	1833300	0.00018333	0.018333
6	2240	87,300 / 100 yr	1920600	0.00019206	0.019206
6	2340	87,300 / 100 yr	2007900	0.00020079	0.020079
6	2440	87,300 / 100 yr	2095200	0.00020952	0.020952
6	2540	87,300 / 100 yr	2182500	0.00021825	0.021825
6	2640	87,300 / 100 yr	2269800	0.00022698	0.022698
6	2740	87,300 / 100 yr	2357100	0.00023571	0.023571
6	2840	87,300 / 100 yr	2444400	0.00024444	0.024444
6	2940	87,300 / 100 yr	2531700	0.00025317	0.025317
6	3040	87,300 / 100 yr	2619000	0.0002619	0.02619
6	3140	87,300 / 100 yr	2706300	0.00027063	0.027063
6	3240	87,300 / 100 yr	2793600	0.00027936	0.027936
6	3340	87,300 / 100 yr	2880900	0.00028809	0.028809
6	3440	87,300 / 100 yr	2968200	0.00029682	0.029682
6	3540	87,300 / 100 yr	3055500	0.00030555	0.030555
6	3640	87,300 / 100 yr	3142800	0.00031428	0.031428
6	3740	87,300 / 100 yr	3230100	0.00032301	0.032301
6	3840	87,300 / 100 yr	3317400	0.00033174	0.033174
6	3940	87,300 / 100 yr	3404700	0.00034047	0.034047
6	4040	87,300 / 100 yr	3492000	0.0003492	0.03492
6	4140	87,300 / 100 yr	3579300	0.00035793	0.035793
6	4240	87,300 / 100 yr	3666600	0.00036666	0.036666
6	4340	87,300 / 100 yr	3753900	0.00037539	0.037539
6	4440	87,300 / 100 yr	3841200	0.00038412	0.038412
6	4540	87,300 / 100 yr	3928500	0.00039285	0.039285
6	4640	87,300 / 100 yr	4015800	0.00040158	0.040158
6	4740	87,300 / 100 yr	4103100	0.00041031	0.041031
6	4840	87,300 / 100 yr	4190400	0.00041904	0.041904
6	4940	87,300 / 100 yr	4277700	0.00042777	0.042777
6	5040	87,300 / 100 yr	4365000	0.0004365	0.04365
6	5140	87,300 / 100 yr	4452300	0.00044523	0.044523
6	5240	87,300 / 100 yr	4539600	0.00045396	0.045396
6	5340	87,300 / 100 yr	4626900	0.00046269	0.046269
6	5440	87,300 / 100 yr	4714200	0.00047142	0.047142
6	5540	87,300 / 100 yr	4801500	0.00048015	0.048015
6	5640	87,300 / 100 yr	4888800	0.00048888	0.048888
6	5740	87,300 / 100 yr	4976100	0.00049761	0.049761
6	5840	87,300 / 100 yr	5063400	0.00050634	0.050634
6	5940	87,300 / 100 yr	5150700	0.00051507	0.051507
6	6040	87,300 / 100 yr	5238000	0.0005238	0.05238
6	6140	87,300 / 100 yr	5325300	0.00053253	0.053253

Stage	Year	Total Stage Hole Size from above Table (mm^2/Hectare)	Total Cumulative Hole Size [1] (mm^2/Hectare)	Fraction of HDPE membrane with Holes [2]	Percentage (%) of HDPE membrane with Holes [3]
6	6240	87,300 / 100 yr	5412600	0.00054126	0.054126
6	6340	87,300 / 100 yr	5499900	0.00054999	0.054999
6	6440	87,300 / 100 yr	5587200	0.00055872	0.055872
6	6540	87,300 / 100 yr	5674500	0.00056745	0.056745
6	6640	87,300 / 100 yr	5761800	0.00057618	0.057618
6	6740	87,300 / 100 yr	5849100	0.00058491	0.058491
6	6840	87,300 / 100 yr	5936400	0.00059364	0.059364
6	6940	87,300 / 100 yr	6023700	0.00060237	0.060237
6	7040	87,300 / 100 yr	6111000	0.0006111	0.06111
6	7140	87,300 / 100 yr	6198300	0.00061983	0.061983
6	7240	87,300 / 100 yr	6285600	0.00062856	0.062856
6	7340	87,300 / 100 yr	6372900	0.00063729	0.063729
6	7440	87,300 / 100 yr	6460200	0.00064602	0.064602
6	7540	87,300 / 100 yr	6547500	0.00065475	0.065475
6	7640	87,300 / 100 yr	6634800	0.00066348	0.066348
6	7740	87,300 / 100 yr	6722100	0.00067221	0.067221
6	7840	87,300 / 100 yr	6809400	0.00068094	0.068094
6	7940	87,300 / 100 yr	6896700	0.00068967	0.068967
6	8040	87,300 / 100 yr	6984000	0.0006984	0.06984
6	8140	87,300 / 100 yr	7071300	0.00070713	0.070713
6	8240	87,300 / 100 yr	7158600	0.00071586	0.071586
6	8340	87,300 / 100 yr	7245900	0.00072459	0.072459
6	8440	87,300 / 100 yr	7333200	0.00073332	0.073332
6	8540	87,300 / 100 yr	7420500	0.00074205	0.074205
6	8640	87,300 / 100 yr	7507800	0.00075078	0.075078
6	8740	87,300 / 100 yr	7595100	0.00075951	0.075951
6	8840	87,300 / 100 yr	7682400	0.00076824	0.076824
6	8940	87,300 / 100 yr	7769700	0.00077697	0.077697
6	9040	87,300 / 100 yr	7857000	0.0007857	0.07857
6	9140	87,300 / 100 yr	7944300	0.00079443	0.079443
6	9240	87,300 / 100 yr	8031600	0.00080316	0.080316
6	9340	87,300 / 100 yr	8118900	0.00081189	0.081189
6	9440	87,300 / 100 yr	8206200	0.00082062	0.082062
6	9540	87,300 / 100 yr	8293500	0.00082935	0.082935
6	9640	87,300 / 100 yr	8380800	0.00083808	0.083808
6	9740	87,300 / 100 yr	8468100	0.00084681	0.084681
6	9840	87,300 / 100 yr	8555400	0.00085554	0.085554
6	9940	87,300 / 100 yr	8642700	0.00086427	0.086427
6	10040	87,300 / 100 yr	8730000	0.000873	0.0873

[1] Total cumulative hole size = Previous total cumulative hole size + Current total stage hole size

[2] Fraction of HDPE geomembrane with holes = Total cumulative hole size / 10,000,000,000 mm^2/Hectare

[3] Percentage (%) of HDPE geomembrane with holes = Fraction of HDPE geomembrane with holes × 100

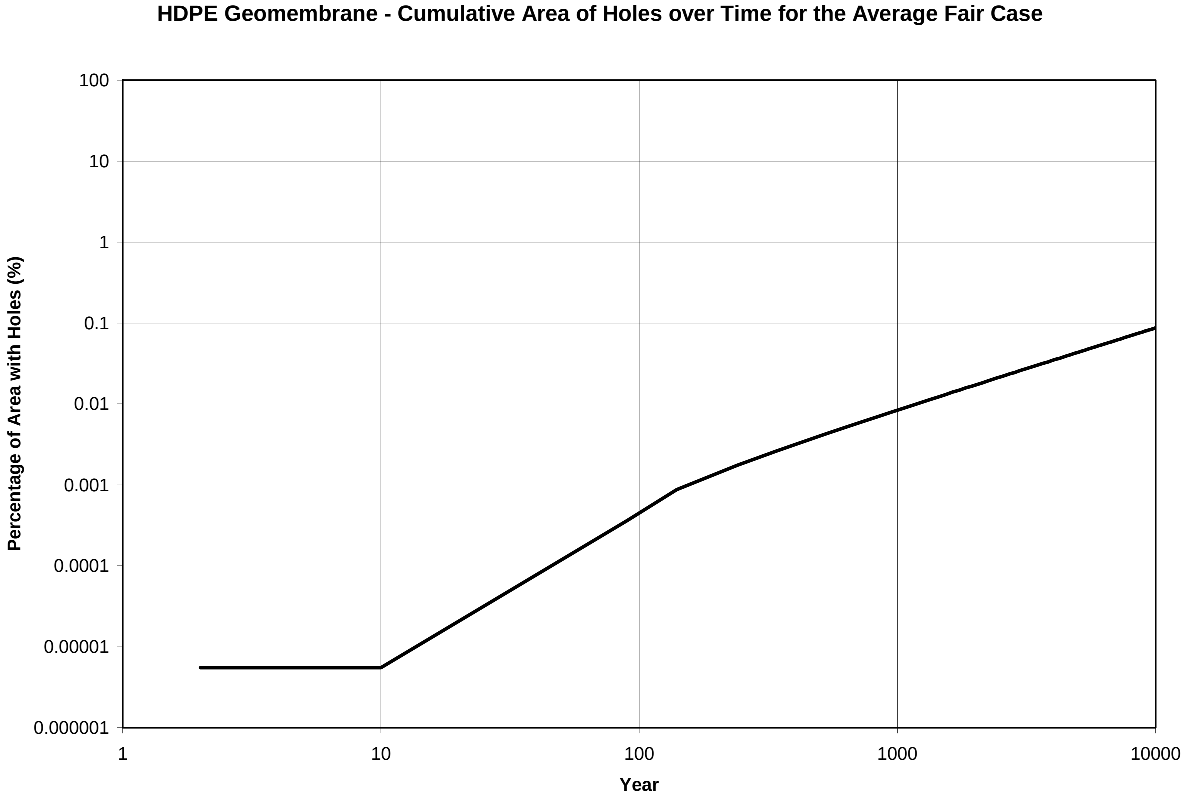

Figure D-2. HDPE Geomembrane – Cumulative Area of Holes over Time for the Average Fair Case

Area of Holes around Years 100, 1,000, and 10,000:

Year	Percentage of HDPE membrane with Holes (%)	Fraction of HDPE membrane with Holes
90	0.000363	0.00000363
140	0.000873	0.00000873
940	0.007857	0.00007857
1,040	0.00873	0.0000873
9,940	0.086427	0.00086427
10,040	0.0873	0.000873

It is assumed that there is a linear relationship between the area of holes for the points immediately around years 100, 1,000, and 10,000, respectively.

Determine percentage of HDPE membrane with holes at years 100, 1,000, and 10,000:

At year 100: $X = 0.000363 + \frac{(100-90)(0.000873-0.000363)}{140-90} = 0.000465\%$

[0.00000465]

At year 1,000: $X = 0.007857 + \frac{(1{,}000 - 940)(0.00873 - 0.007857)}{1{,}040 - 940} = 0.00838\%$

[0.0000838]

At year 10,000: $X = 0.086427 + \frac{(10{,}000 - 9{,}940)(0.0873 - 0.086427)}{10{,}040 - 9{,}940} = 0.0870\%$

[0.000870]

The HELP model allows the input of up to 999,999 one square centimeter installation defects per acre for a geomembrane liner. So the percentage of holes that the HELP model allows to be input is 2.47% (This means that the HELP model can accommodate the anticipated HDPE geomembrane degradation):

$$X = \frac{999{,}999\ cm^2 / acre}{4.04686E07\ cm^2 / acre} \times 100 = 2.47\%\ [0.0247]$$

Equivalent number of one square centimeter installation defects per acre at year 100, 1,000, and 10,000:

At year 100: # of 1-cm^2 holes/acre = 0.00000465 × 4.04686E07 cm^2/acre = 188.2 cm^2/acre ≈ 189 1-cm^2 holes/acre
At year 1,000: # of 1-cm^2 holes/acre = 0.0000838 × 4.04686E07 cm^2/acre = 3,391.3 cm^2/acre ≈ 3,392 1-cm^2 holes/acre
At year 100: # of 1-cm^2 holes/acre = 0.000870 × 4.04686E07 cm^2/acre = 35,207.7 cm^2/acre ≈ 35,208 1-cm^2 holes/acre

Summary of holes in the HDPE geomembrane at years 100, 1,000, and 10,000:

Parameter	Year 100	Year 1,000	Year 10,000
Area of Holes in the HDPE (%)	0.000465	0.00838	0.0870
Fractional Area of Holes in the HDPE	0.00000465	0.0000838	0.000870
Equivalent # of 1-cm^2 holes/acre in the HDPE	189	3,392	35,208

D-4.3 CONCRETE AND SALTSTONE DEGRADATION

It is assumed that the vault concrete and Saltstone will degrade over time as outlined by Cook (2004). Cook (2004) assumes that the saturated hydraulic conductivity increases over time, while the porosity and effective diffusion coefficient are assumed to remain constant over time.

Year	Concrete			Saltstone		
	K_{sat} (cm/s)	n [4]	D_e (cm^2/yr)	K_{sat} (cm/s)	n [4]	D_e (cm^2/yr)
100 [1]	1.00E-12	0.19	0.315	1.00E-11	0.42	0.158
1,000 [2]	3.16E-11	0.19	0.315	1.00E-10	0.42	0.158
10,000 [3]	1.00E-09	0.19	0.315	1.00E-09	0.42	0.158

K_{sat} = saturated hydraulic conductivity; n = porosity; D_e = effective diffusion coefficient

[1] Time interval TI01 from Cook (2004)

[2] Time interval TI04 from Cook (2004)

[3] Time interval TI08 from Cook (2004)

[4] Porosity taken from WSRC 1993 and WSRC 2002

D-4.4 HELP MODEL WATER FLUX ESTIMATES

The HELP model is a quasi-two-dimensional water balance model designed to conduct landfill water balance analyses. The model requires the input of weather, soil, and design data. It provides estimates of runoff, evapotranspiration, lateral drainage, vertical percolation, hydraulic head, and water storage for the evaluation of various landfill designs. Personnel at the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi developed the HELP model, under an interagency agreement with the EPA. HELP model version 3.07, issued on November 1, 1997, is the latest version of the model available from the Waterways Experiment Station (USEPA 1994a and USEPA 1994b). (WSRC 2002)

The following input weather files from Phifer and Nelson (2003) were utilized as input to the HELP model runs:

- ZPREC.D4
- ZTEMP.D7
- ZSOLAR.D13
- ZEVAP.D11

The following HELP model soil and design data input files from Phifer (2003) were utilized as the basis for the input files produced herein:

- Input data file ZMSED1.D10 from Appendix G of Phifer (2003) was utilized as the basis for soil layers 1 through 8 for the year 100 input files produced herein.
- Input data file ZMSED4.D10 from Appendix J of Phifer (2003) was utilized as the basis for soil layers 1 through 8 for the year 1,000 input files produced herein.
- Input data file ZMSED8.D10 from Appendix N of Phifer (2003) was utilized as the basis for soil layers 1 through 8 for the year 10,000 input files produced herein.

The HELP model soil and design data for soil layers 9 through 13 were based upon the information provided in Sections D-4.1, D-4.2, and D-4.3, herein, and the field capacity and wilting point for concrete and Saltstone provided in Phifer and Nelson (2003).

The HELP model soil and design data input files utilized to produce the infiltration estimates are provided in the following tables located at the end of this appendix:

- Table D-1, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (100 Years)
- Table D-2, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (100 Years)
- Table D-3, Infiltration through Degraded Closure Cap without Vault 2 (100 Years)
- Table D-4, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (1,000 Years)
- Table D-5, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (1,000 Years)
- Table D-6, Infiltration through Degraded Closure Cap without Vault 2 (1,000 Years)
- Table D-7, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (10,000 Years)
- Table D-8, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (10,000 Years)
- Table D-9, Infiltration through Degraded Closure Cap without Vault 2 (10,000 Years)

Summary infiltration estimates for years 100, 1,000, and 10,000:

Infiltration Case	Infiltration at year 100 (inches/year)	Infiltration at year 1,000 (inches/year)	Infiltration at year 10,000 (inches/year)
Degraded Closure Cap and Vault 2 with HDPE geomembrane [1]	0.00000	0.00017	0.01281
Degraded Closure Cap and Vault 2 without HDPE geomembrane [1]	0.00001	0.00035	0.01385
Degraded Closure Cap without Vault 2 [2]	0.41699	12.03710	14.07465

[1] The highest value of infiltration estimated for the 8 inch concrete roof or the 24 inch concrete floor was utilized as the infiltration out the bottom of the vault.

[2] The highest value of infiltration estimated for the upper GCL or lower backfill was utilized as the infiltration through the closure cap.

D-4.5 NITRATE DIFFUSION FLUX OUT VAULT #2 SIDE

A conservative estimate of the nitrate diffusion flux out the side of Vault #2 has been made both with and without a HDPE geomembrane, based upon a one-dimensional formulation of Fick's First Law modified for diffusion in porous media (Rumer and Mitchell 1995):

$J = \frac{nD_m C_o}{\tau L}$ where J = flux; n = porosity; D_m = molecular diffusion coefficient in water; C_o = initial pore water concentration; τ = tortuosity; L = thickness

$D_e = \frac{D_m}{\tau}$ where D_e = effective diffusion coefficient in porous media

$$J = \frac{nD_eC_o}{L}$$

A further modification of the above diffusion equation involves the addition of the combined diffusion through a HDPE geomembrane/concrete diffusion barrier. It is assumed that nitrate does not diffuse through intact portions of the HDPE geomembrane and that any diffusion through the HDPE only occurs at holes in the HDPE. Therefore the above equation is further modified by multiplying by the fractional area through which diffusion can occur (i.e. the fractional area of holes in the HDPE geomembrane). The equation becomes:

$$J = \frac{A_f nD_eC_o}{L}$$ where A_f = fractional area of holes in the HDPE geomembrane

The following assumptions have been made to estimate the nitrate diffusion flux out the side of the vault:

- It is assumed that Fick's First Law can adequately represent nitrate diffusion through the diffusion barriers,
- Nitrate concentrations of the Saltstone pore water remains constant at 47,234 mg/L nitrate/nitrite as nitrogen (i.e. constant over time) (WSRC 2002),
- Steady-state conditions,
- No advection through the walls,
- Nitrate is conservative (i.e. non-reactive species with a $K_d = 0$) (WSRC 1992),
- It is assumed that nitrate does not diffuse through intact portions of the HDPE geomembrane and that any diffusion through the HDPE only occur at holes in the HDPE,
- Saturated conditions, and
- Flushing boundary condition (i.e. nitrate concentration of 0 at the boundary due to water flux which transports all nitrate away).

The following are the primary input parameter values for these calculations:

- Fractional area of holes in the HDPE geomembrane (A_f) at 100 years = 0.00000465
- Fractional area of holes in the HDPE geomembrane (A_f) at 1,000 years = 0.0000838
- Fractional area of holes in the HDPE geomembrane (A_f) at 10,000 years = 0.000870
- Fractional area of holes in the HDPE geomembrane (A_f) = 1 for cases where the HDPE is not present
- Porosity of concrete (n) = 0.19
- Effective diffusion coefficient of concrete (D_e) = 0.315 cm^2/yr
- Nitrate concentration in Saltstone pore water (C_o) = 47,234 mg/L nitrate/nitrite as nitrogen
- Thickness of concrete side wall (L) = 8 inches

The nitrate diffusion flux calculation for the cases where the HDPE geomembrane is not present (i.e. only 8 inches of concrete) is the same at years 100, 1,000, and 10,000:

$$J = \frac{A_f n D_e C_o}{L} = \frac{(1)(0.19)\left(0.315\ cm^2/yr \times m^2/10{,}000\ cm^2\right)\left(47{,}234\ mg/L \times 1000\ L/m^3\right)}{8\ in \times ft/12\ in \times 0.3048\ m/ft} \mathrm{J}$$

= 1,391.2 mg/m^2 year

The nitrate diffusion flux calculation for vault with HDPE geomembrane at year 100:

$$J = \frac{A_f n D_e C_o}{L} = \frac{(0.00000465)(0.19)\left(0.315\ cm^2/yr \times m^2/10{,}000\ cm^2\right)\left(47{,}234\ mg/L \times 1000\ L/m^3\right)}{8\ in \times ft/12\ in \times 0.3048\ m/ft}$$

J = 0.0065 mg/m^2 year

The nitrate diffusion flux calculation for vault with HDPE geomembrane at year 1,000:

$$J = \frac{A_f n D_e C_o}{L} = \frac{(0.0000838)(0.19)\left(0.315\ cm^2/yr \times m^2/10{,}000\ cm^2\right)\left(47{,}234\ mg/L \times 1000\ L/m^3\right)}{8\ in \times ft/12\ in \times 0.3048\ m/ft}$$

J = 0.12 mg/m^2 year

The nitrate diffusion flux calculation for vault with HDPE geomembrane at year 10,000:

$$J = \frac{A_f n D_e C_o}{L} = \frac{(0.000870)(0.19)\left(0.315\ cm^2/yr \times m^2/10{,}000\ cm^2\right)\left(47{,}234\ mg/L \times 1000\ L/m^3\right)}{8\ in \times ft/12\ in \times 0.3048\ m/ft}$$

J = 1.21 mg/m^2 year

Summary nitrate diffusion flux out the side of Vault #2 both with and without the HDPE geomembrane at years 100, 1,000, and 10,000:

Flux Case	Flux at year 100 (mg/m^2 year)	Flux at year 1,000 (mg/m^2 year)	Flux at year 10,000 (mg/m^2 year)
8 inch Concrete	1,391.2	1,391.2	1,391.2
8 inch Concrete and 100 mil HDPE geomembrane	0.0065	0.12	1.21

D-4.6 NITRATE GROUNDWATER CONCENTRATION CALCULATIONS

The following are the primary assumptions associated with the calculation of the nitrate groundwater concentration:

- It is assumed that the water flux out the bottom of the Cylindrical Vault contains nitrate concentrations equal to that of the Saltstone pore fluid (i.e. 47,234 mg/L nitrate/nitrite as nitrogen (WSRC 2002)). Diffusion is not considered out the bottom.
- It is assumed that the water flux around the Cylindrical Vault contains nitrate due to diffusion out the side of the vault. Advection is not considered out the sides.
- It is assumed that diffusion out the top of the vault is insignificant and can be ignored.
- It is assumed that a typical monitoring well has a screen length of 10 feet. It is further assumed that it is regulatorily satisfactory if the average nitrate concentration over a 10-foot screen interval is less than 10 mg/L of nitrate as nitrogen, that the 10-foot screen interval represents a 2500-foot infiltration interval on the ground surface parallel to the direction of groundwater flow, and that the well has a ten-foot radius of influence (i.e. the monitoring well intercepts a 20-foot wide area perpendicular to the

groundwater flow direction). This means that the mass of nitrate that enters the 20-foot by 2500-foot area (50,000 ft^2) per a given time period divided by the volume of water that enters the area over the same given time period equals the nitrate concentration of the 10-foot screen interval.

- It is assumed that the closure cap has a 3% slope over a 450-foot slope length and that it entirely covers the 2500-foot footprint that feeds into the 10-foot screen interval.

The fourth primary assumption above is based upon Section 5.0 of the report entitled “Saltstone Landfill Design Equivalency Demonstration (U)” (WSRC 2002). Within WSRC 2002 Section 5.0, it was calculated that infiltration from a 125-foot Saltstone footprint along the direction of groundwater flow would become a thickness of approximately 0.5 feet within the water table aquifer downgradient of the Saltstone vault. Within WSRC 2002 Section 5.0, it was assumed that a typical monitoring well has a screen length of 10 feet and that it is regulatorily satisfactory if the average nitrate concentration over the 10-foot screen interval is less than 10 mg/L of nitrate as nitrogen. Based upon this information a thickness of 10 feet within the water table aquifer would result from infiltration from a 2500-foot footprint along the direction of groundwater flow:

Footprint length = 125 ft × (10 ft ÷ 0.5 ft) = 2500 ft

As shown in Figures D-3 and D-4 the estimated nitrate concentration at monitoring well ABC is the results of the mass of nitrate resulting from diffusion out Vault Wall Area C and advection out the Vault Floor Area B over a year time period divided by the volume of water infiltration through Area A and Vault Floor Area B over a year time period. As shown in Figures D-3 and D-4 the estimated nitrate concentration at monitoring well DEF is the result of nitrate diffusing out of Vault Wall Area F and advection out of Vault Floor Area E over a one-year time period divided by the volume of water infiltration through Area D and Vault Floor Area E over a one-year time period.

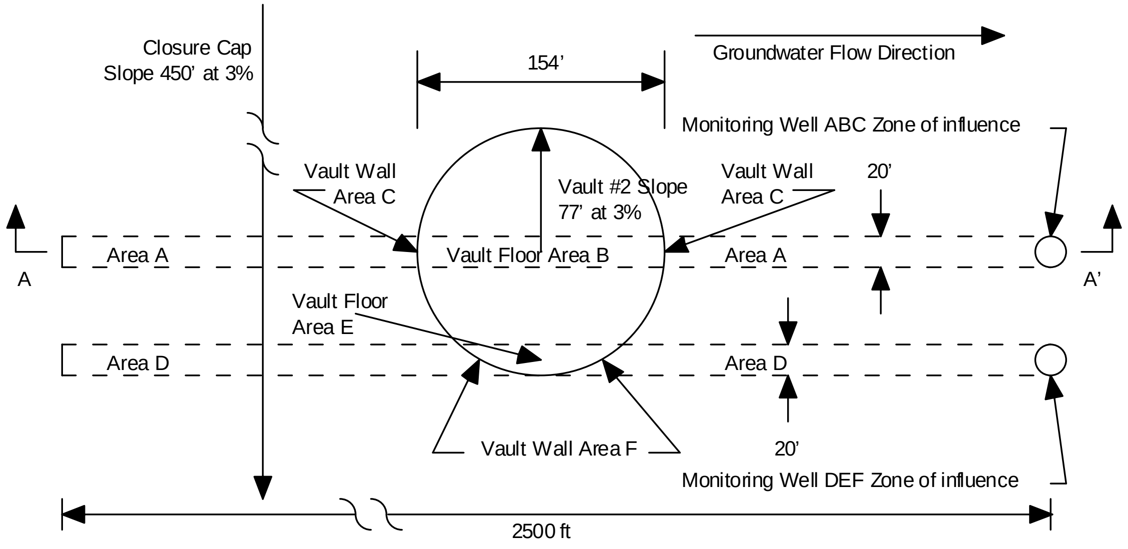

Figure D-3. Vault #2 Plot Plan relative to groundwater flow and closure cap

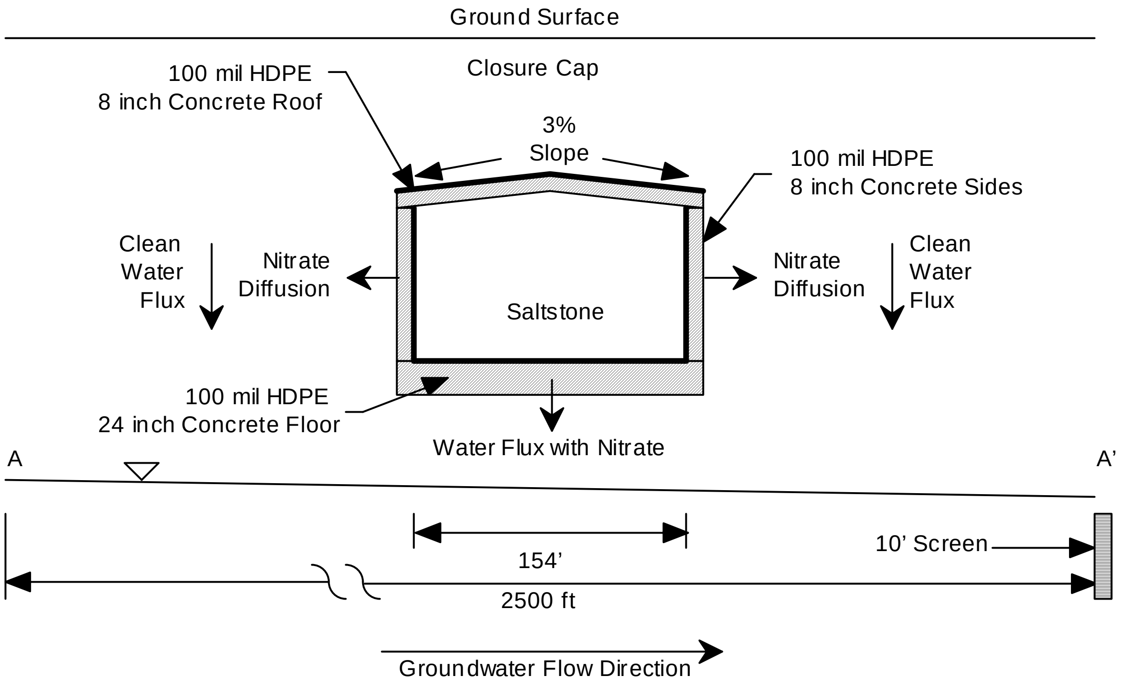

Figure D-4. Section AA´ to Plot Plan

Find areas of Area A, Vault Floor Area B, Area D, and Vault Floor Area E:

The areas of Area A and Area B will be estimated ignoring the arc of the vault footprint (see Figures D-3 and D-4).

Area A = 20' × (2500' – 154') = 46,920 ft^2
Vault Floor Area B = 20' × 154' = 3080 ft^2

The areas of Area D and Vault Floor Area E will be estimated taking into account the arc of the vault footprint (see Figures D-3 and D-4).

Given R=77' and h=20' (see Figure D-5 below) find Vault Floor Area E:

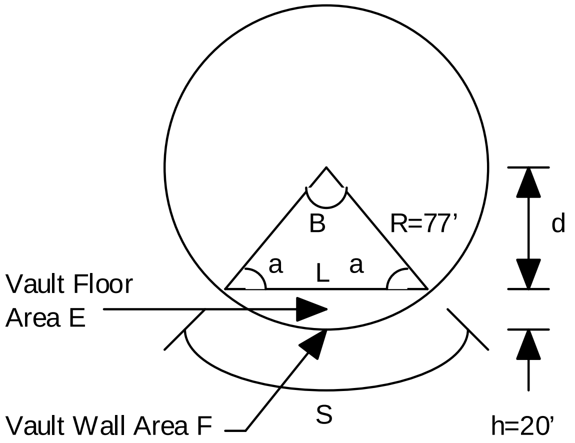

Figure D-5. Vault Floor Area E

d = R – h = 77’ – 20’ = 57’

$$L = 2\sqrt{R^2 - d^2} = 2\sqrt{(77')^2 - (57')^2} = 103.54'$$

sin a = d/R = 57’/77’ = 0.74

a = 47.75°

B = 180° – 2a = 180° – 2(47.75°) = 84.5° = 1.475 radians (180° = π radians)

S = RB = 77’(1.475) = 113.58’

Sector Area = ½ R^2B = ½ $(77')^2$ (1.475) = 4372.6 ft^2

Triangle Area = ½ Ld = ½ (103.54’) (57’) = 2950.9 ft^2

Vault Floor Area E = Sector Area – Triangle Area = 4372.6 ft^2 - 2950.9 ft^2 = 1421.7 ft^2

Area D = (20’ × 2500’) – Vault Floor Area E = 50,000 ft^2 - 1421.7 ft^2 = 48,578.3 ft^2

Find areas of vault wall areas C and F through which diffusion occurs that contributes to the concentration of nitrate to monitoring wells ABC and DEF, respectively:

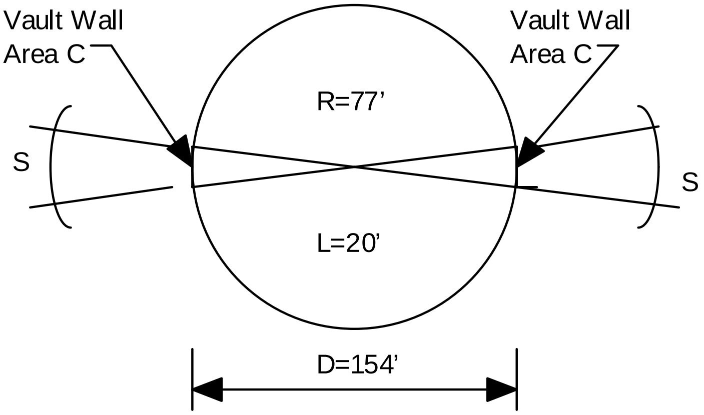

Figure D-6. Vault wall area C contributing to monitoring well ABC

$$d = \tfrac{1}{2}\sqrt{4R^2 - L^2} = \tfrac{1}{2}\sqrt{4(77')^2 - (20')^2} = 76.3'$$

$$S = D\cos^{-1}\frac{d}{R} = 154'\cos^{-1}\frac{76.3'}{77'} = 20.78'$$, where 76.3’/77’ is in radians

Vault wall area C = 2S × vault height, where vault height = 20’

Vault wall area C = 2 × 20.78’ × 20’ = 831.2 ft^2

Vault wall area F contributing to monitoring well DEF:

Vault wall area F = S × vault height, where S = 113.35’ and vault height = 20’

Vault wall area F = 113.58’ × 20’ = 2271.6 ft^2

Summary areas contributing to monitoring wells ABC and DEF:

Monitoring Well	Location	Area (ft^2)
ABC	Area A	46,920
	Vault Floor Area B	3,080
	Vault Wall Area C	831.2

DEF	Area D	48,578.3
	Vault Floor Area E	1,421.7
	Vault Wall Area C	2,271.6

Summary infiltration estimates for years 100, 1,000, and 10,000:

Infiltration Case	Infiltration at year 100 (inches/year)	Infiltration at year 1,000 (inches/year)	Infiltration at year 10,000 (inches/year)
Degraded Closure Cap and Vault 2 with HDPE geomembrane	0.00000	0.00017	0.01281
Degraded Closure Cap and Vault 2 without HDPE geomembrane	0.00001	0.00035	0.01385
Degraded Closure Cap without Vault 2	0.41699	12.03710	14.07465

Summary nitrate diffusion flux out the side of Vault #2 both with and without the HDPE geomembrane at years 100, 1,000, and 10,000:

Flux Case	Flux at year 100 (mg/m^2 year)	Flux at year 1,000 (mg/m^2 year)	Flux at year 10,000 (mg/m^2 year)
8 inch Concrete	1,391.2	1,391.2	1,391.2
8 inch Concrete and 100 mil HDPE geomembrane	0.0065	0.12	1.21

As stated previously it is assumed that the water flux out the bottom of the Cylindrical Vault contains nitrate concentrations equal to that of the Saltstone pore fluid (i.e. 47,234 mg/L nitrate/nitrite as nitrogen (WSRC 2002)).

Estimate nitrate concentration in monitoring well ABC at year 100 for Vault 2 with a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area A	46,920	0.41699	-	0
Vault Floor Area B	3,080	0	-	47,234
Vault Wall Area C	831.2	-	0.0065	-

Water Volume = [46,920 ft^2 × (0.41699 inches/yr × 1 ft/12 inches)] × 28.31687 L/ft^3
Water Volume = 46,168.7 L/yr

Nitrate Mass only comes from diffusion out the sides in this case since there is no water flux through the vault floor.

Nitrate Mass = 831.2 ft^2 × 0.0929 m^2/ft^2 × 0.0065 mg/m^2 year = 0.502 mg/year
Nitrate Concentration = 0.502 mg/year / 46,168.7 L/yr = 1.09E-05 mg/L

Estimate nitrate concentration in monitoring well DEF at year 100 for Vault 2 with a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area D	48,578.3	0.41699	-	0
Vault Floor Area E	1,421.7	0	-	47,234
Vault Wall Area F	2,271.6	-	0.0065	-

Water Volume = [48,578.3 ft^2 × (0.41699 inches/yr × 1 ft/12 inches)] × 28.31687 L/ft^3
Water Volume = 47,800.4 L/yr

Nitrate Mass only comes from diffusion out the sides in this case since there is no water flux through the vault floor.

Nitrate Mass = 2,271.6 ft^2 × 0.0929 m^2/ft^2 × 0.0065 mg/m^2 year = 1.37 mg/year
Nitrate Concentration = 1.37 mg/year / 47,800.4 L/yr = 2.87E-05 mg/L

Estimate nitrate concentration in monitoring well ABC at year 100 for Vault 2 without a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area A	46,920	0.41699	-	0
Vault Floor Area B	3,080	0.00001	-	47,234
Vault Wall Area C	831.2	-	1,391.2	-

Water Volume = [(46,920 ft^2 × (0.41699 inches/yr × 1 ft/12 inches)) + (3,080 ft^2 × (0.00001 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 46,168.8 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [831.2 ft^2 × 0.0929 m^2/ft^2 × 1,391.2 mg/m^2 year] + [(3,080 ft^2 × (0.00001 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 110,859.3 mg/year
Nitrate Concentration = 110,859.3 mg/year / 46,168.8 L/yr = 2.4 mg/L

Estimate nitrate concentration in monitoring well DEF at year 100 for Vault 2 without a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area D	48,578.3	0.41699	-	0
Vault Floor Area E	1,421.7	0.00001	-	47,234
Vault Wall Area F	2,271.6	-	1,391.2	-

Water Volume = [(48,578.3 ft^2 × (0.41699 inches/yr × 1 ft/12 inches)) + (1,421.7 ft^2 × (0.00001 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 47,800.5 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [2,271.6 ft^2 × 0.0929 m^2/ft^2 × 1,391.2 mg/m^2 year] + [(1,421.7 ft^2 × (0.00001 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 295,171.8 mg/year
Nitrate Concentration = 295,171.8 mg/year / 47,800.5 L/yr = 6.2 mg/L

Estimate nitrate concentration in monitoring well ABC at year 1,000 for Vault 2 with a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area A	46,920	12.03710	-	0
Vault Floor Area B	3,080	0.00017	-	47,234
Vault Wall Area C	831.2	-	0.12	-

Water Volume = [(46,920 ft^2 × (12.03710 inches/yr × 1 ft/12 inches)) + (3,080 ft^2 × (0.00017 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 1,332,736.4 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [831.2 ft^2 × 0.0929 m^2/ft^2 × 0.12 mg/m^2 year] + [(3,080 ft^2 × (0.00017 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 58,369.7 mg/year
Nitrate Concentration = 58,369.7 mg/year / 1,332,736.4 L/yr = 0.044 mg/L

Estimate nitrate concentration in monitoring well DEF at year 1,000 for Vault 2 with a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area D	48,578.3	12.03710	-	0
Vault Floor Area E	1,421.7	0.00017	-	47,234
Vault Wall Area F	2,271.6	-	0.12	-

Water Volume = [(48,578.3 ft^2 × (12.03710 inches/yr × 1 ft/12 inches)) + (1,421.7 ft^2 × (0.00017 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 1,379,838.8 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [2,271.6 ft^2 × 0.0929 m^2/ft^2 × 0.12 mg/m^2 year] + [(1,421.7 ft^2 × (0.00017 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 26,964.0 mg/year

Nitrate Concentration = 26,964.0 mg/year / 1,379,838.8 L/yr = 0.020 mg/L

Estimate nitrate concentration in monitoring well ABC at year 1,000 for Vault 2 without a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area A	46,920	12.03710	-	0
Vault Floor Area B	3,080	0.00035	-	47,234
Vault Wall Area C	831.2	-	1,391.2	-

Water Volume = [(46,920 ft^2 × (12.03710 inches/yr × 1 ft/12 inches)) + (3,080 ft^2 × (0.00035 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 1,332,737.8 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [831.2 ft^2 × 0.0929 m^2/ft^2 × 1,391.2 mg/m^2 year] + [(3,080 ft^2 × (0.00035 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 227,580.1 mg/year
Nitrate Concentration = 227,580.1 mg/year / 1,332,737.8 L/yr = 0.17 mg/L

Estimate nitrate concentration in monitoring well DEF at year 1,000 for Vault 2 without a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area D	48,578.3	12.03710	-	0
Vault Floor Area E	1,421.7	0.00035	-	47,234
Vault Wall Area F	2,271.6	-	1,391.2	-

Water Volume = [(48,578.3 ft^2 × (12.03710 inches/yr × 1 ft/12 inches)) + (1,421.7 ft^2 × (0.00035 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 1,379,839.4 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [2,271.6 ft^2 × 0.0929 m^2/ft^2 × 1,391.2 mg/m^2 year] + [(1,421.7 ft^2 × (0.00035 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 349,049.1 mg/year
Nitrate Concentration = 349,049.1 mg/year / 1,379,839.4 L/yr = 0.25 mg/L

Estimate nitrate concentration in monitoring well ABC at year 10,000 for Vault 2 with a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area A	46,920	14.07465	-	0
Vault Floor Area B	3,080	0.01281	-	47,234
Vault Wall Area C	831.2	-	1.21	-

Water Volume = [(46,920 ft^2 × (14.07465 inches/yr × 1 ft/12 inches)) + (3,080 ft^2 × (0.01281 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 1,558,423.7 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [831.2 ft^2 × 0.0929 m^2/ft^2 × 1.21 mg/m^2 year] + [(3,080 ft^2 × (0.01281 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 4,397,722.3 mg/year
Nitrate Concentration = 4,397,722.3 mg/year / 1,558,423.7 L/yr = 2.8 mg/L

Estimate nitrate concentration in monitoring well DEF at year 10,000 for Vault 2 with a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area D	48,578.3	14.07465	-	0
Vault Floor Area E	1,421.7	0.01281	-	47,234
Vault Wall Area F	2,271.6	-	1.21	-

Water Volume = [(48,578.3 ft^2 × (14.07465 inches/yr × 1 ft/12 inches)) + (1,421.7 ft^2 × (0.01281 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 1,613,449.9 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [2,271.6 ft^2 × 0.0929 m^2/ft^2 × 1.21 mg/m^2 year] + [(1,421.7 ft^2 × (0.01281 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 2,030,160.8 mg/year
Nitrate Concentration = 2,030,160.8 mg/year / 1,613,449.9 L/yr = 1.26 mg/L

Estimate nitrate concentration in monitoring well ABC at year 10,000 for Vault 2 without a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area A	46,920	14.07465	-	0
Vault Floor Area B	3,080	0.01385	-	47,234
Vault Wall Area C	831.2	-	1,391.2	-

Water Volume = [(46,920 ft^2 × (14.07465 inches/yr × 1 ft/12 inches)) + (3,080 ft^2 × (0.01385 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3
Water Volume = 1,558,429.6 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [831.2 ft^2 × 0.0929 m^2/ft^2 × 1,391.2 mg/m^2 year] + [(3,080 ft^2 × (0.01385 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 4,862,083.6 mg/year
Nitrate Concentration = 4,862,083.6 mg/year / 1,558,429.6 L/yr = 3.12 mg/L

Estimate nitrate concentration in monitoring well DEF at year 10,000 for Vault 2 without a HDPE geomembrane:

Pertinent parameter values:

Location	Area (ft^2)	Infiltration (inches/yr)	Diffusion Flux (mg/m^2 year)	Concentration (mg/L nitrate/nitrite as nitrogen)
Area D	48,578.3	14.07465	-	0
Vault Floor Area E	1,421.7	0.01385	-	47,234
Vault Wall Area F	2,271.6	-	1,391.2	-

Water Volume = [(48,578.3 ft^2 × (14.07465 inches/yr × 1 ft/12 inches)) + (1,421.7 ft^2 × (0.01385 inches/yr × 1 ft/12 inches))] × 28.31687 L/ft^3

Water Volume = 1,613,453.4 L/yr

Nitrate Mass comes from both diffusion out the sides and water flux through the vault floor.

Nitrate Mass = [2,271.6 ft^2 × 0.0929 m^2/ft^2 × 1,391.2 mg/m^2 year] + [(1,421.7 ft^2 × (0.01385 inches/yr × 1 ft/12 inches)) × 28.31687 L/ft^3) × 47,234 mg/L] = 2,488,293.8 mg/year
Nitrate Concentration = 2,488,293.8 mg/year / 1,613,453.4 L/yr = 1.54 mg/L

Summary nitrate groundwater concentrations:

Year	Nitrate in Well ABC for Vault with HDPE (mg/L, nitrate/nitrite as nitrogen)	Nitrate in Well DEF for Vault with HDPE (mg/L, nitrate/nitrite as nitrogen)	Nitrate in Well ABC for Vault without HDPE (mg/L, nitrate/nitrite as nitrogen)	Nitrate in Well DEF for Vault without HDPE (mg/L, nitrate/nitrite as nitrogen)
100	1.09E-05	2.87E-05	2.4	6.2
1,000	0.044	0.020	0.17	0.25
10,000	2.8	1.26	3.12	1.54

Nitrate groundwater concentration evaluation:

Year	Maximum Contaminant Level (mg/L, nitrate as nitrogen)	Nitrate in Well for Vault without HDPE (mg/L, nitrate/nitrite as nitrogen)	Nitrate in Well for Vault with HDPE (mg/L, nitrate/nitrite as nitrogen)	Ratio of Nitrate for Vault without HPDE to with HDPE
100	10	6.2	2.87E-05	216,027.9
1,000	10	0.25	0.044	5.7
10,000	10	3.12	2.8	1.1

D-5 REFERENCES

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D-6 HELP MODEL INPUT

The following HELP model input tables are provided:

- Table D-1, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (100 Years)
- Table D-2, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (100 Years)
- Table D-3, Infiltration through Degraded Closure Cap without Vault 2 (100 Years)
- Table D-4, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (1,000 Years)
- Table D-5, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (1,000 Years)
- Table D-6, Infiltration through Degraded Closure Cap without Vault 2 (1,000 Years)
- Table D-7, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (10,000 Years)
- Table D-8, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (10,000 Years)
- Table D-9, Infiltration through Degraded Closure Cap without Vault 2 (10,000 Years)

Table D-1, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (100 Years)
HELP Model Input Data File: V2F100.D10; and Output File: V2F100ou.OUT (input file based upon previous file ZMSED1.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.002 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	77 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 60.0	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	3 (barrier soil liner)
Lower Backfill	7	1 (vertical percolation layer)
Lower Drainage Layer	8	2 (lateral drainage layer)
Roof HDPE	9	4 (flexible membrane liner)
Concrete Vault Roof	10	3 (barrier soil liner)
Saltstone	11	1 (vertical percolation layer)
Floor HDPE	12	4 (flexible membrane liner)
Concrete Vault Floor	13	3 (barrier soil liner)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	5.980		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.06	0.056	0.052	0.056
4	1	12		0.37	0.236	0.133	0.236
5	2	12		0.38	0.084	0.016	0.084
6	3	0.2		0.75	0.747	0.40	0.75
7	1	58.57		0.37	0.24	0.136	0.24
8	2	24		0.38	0.08	0.013	0.08
9	4	0.1					
10	3	8		0.19	0.18	0.17	0.19
11	1	240		0.42	0.41	0.40	0.41
12	4	0.1					
13	3	24		0.19	0.18	0.17	0.19

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	3.97E-04					
4	1	1.20E-04					
5	2	8.60E-02	77	3			
6	3	5.00E-09					
7	1	1.00E-04					
8	2	1.00E-01	77	3			
9	4	2.00E-13					
10	3	1.00E-12					
11	1	1.00E-11					
12	4	2.00E-13					
13	3	1.00E-12					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	3				
7	1				
8	2				
9	4	0	189	3	
10	3				
11	1				
12	4	0	189	3	
13	3				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

* The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-2, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (100 Years)
HELP Model Input Data File: V2100.D10; and Output File: V2100out.OUT (input file based upon previous file ZMSED1.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.002 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	77 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 60.0	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	3 (barrier soil liner)
Lower Backfill	7	1 (vertical percolation layer)
Lower Drainage Layer	8	2 (lateral drainage layer)
Concrete Vault Roof	9	3 (barrier soil liner)
Saltstone	10	1 (vertical percolation layer)
Concrete Vault Floor	11	3 (barrier soil liner)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	5.980		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.06	0.056	0.052	0.056
4	1	12		0.37	0.236	0.133	0.236
5	2	12		0.38	0.084	0.016	0.084
6	3	0.2		0.75	0.747	0.40	0.75
7	1	58.57		0.37	0.24	0.136	0.24
8	2	24		0.38	0.08	0.013	0.08
9	3	8		0.19	0.18	0.17	0.19
10	1	240		0.42	0.41	0.40	0.41
11	3	24		0.19	0.18	0.17	0.19

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	3.97E-04					
4	1	1.20E-04					
5	2	8.60E-02	77	3			
6	3	5.00E-09					
7	1	1.00E-04					
8	2	1.00E-01	77	3			
9	3	1.00E-12					
10	1	1.00E-11					
11	3	1.00E-12					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	3				
7	1				
8	2				
9	3				
10	1				
11	3				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

* The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-3, Infiltration through Degraded Closure Cap without Vault 2 (100 Years)
HELP Model Input Data File: V2C100.D10; and Output File: V2C100ou.OUT (input file based upon previous file ZMSED1.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.01 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	450 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 54.4	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	3 (barrier soil liner)
Lower Backfill	7	1 (vertical percolation layer)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	5.980		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.06	0.056	0.052	0.056
4	1	12		0.37	0.236	0.133	0.236
5	2	12		0.38	0.084	0.016	0.084
6	3	0.2		0.75	0.747	0.40	0.75
7	1	58.57		0.37	0.24	0.136	0.24

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	3.97E-04					
4	1	1.20E-04					
5	2	8.60E-02	450	3			
6	3	5.00E-09					
7	1	1.00E-04					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	3				
7	1				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

* The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-4, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (1,000 Years)
HELP Model Input Data File: V2F1K.D10; and Output File: V2F1Kout.OUT (input file based upon previous file ZMSED4.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.002 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	77 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 60.0	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	4 (flexible membrane liner)
Lower Backfill	7	1 (vertical percolation layer)
Lower Drainage Layer	8	2 (lateral drainage layer)
Roof HDPE	9	4 (flexible membrane liner)
Concrete Vault Roof	10	3 (barrier soil liner)
Saltstone	11	1 (vertical percolation layer)
Floor HDPE	12	4 (flexible membrane liner)
Concrete Vault Floor	13	3 (barrier soil liner)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	5.8		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.062	0.0574	0.0526	0.0574
4	1	12		0.372	0.204	0.109	0.204
5	2	12		0.378	0.116	0.040	0.116
6	4	0.2					
7	1	58.57		0.37	0.24	0.136	0.24
8	2	24		0.374	0.0851	0.0203	0.0851
9	4	0.1					
10	3	8		0.19	0.18	0.17	0.19
11	1	240		0.42	0.41	0.40	0.41
12	4	0.1					
13	3	24		0.19	0.18	0.17	0.19

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	4.01E-04					
4	1	4.60E-04					
5	2	2.10E-02	77	3			
6	4	5.00E-09					
7	1	1.00E-04					
8	2	9.61E-02	77	3			
9	4	2.00E-13					
10	3	3.16E-11					
11	1	1.00E-10					
12	4	2.00E-13					
14	3	3.16E-11					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	4	0	59,458	1	
7	1				
8	2				
9	4	0	3,392	3	
10	3				
11	1				
12	4	0	3,392	3	
13	3				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

* The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-5, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (1,000 Years)
HELP Model Input Data File: V21K.D10; and Output File: V21Kout.OUT (input file based upon previous file ZMSED4.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.002 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	77 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 60.0	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	4 (flexible membrane liner)
Lower Backfill	7	1 (vertical percolation layer)
Lower Drainage Layer	8	2 (lateral drainage layer)
Concrete Vault Roof	9	3 (barrier soil liner)
Saltstone	10	1 (vertical percolation layer)
Concrete Vault Floor	11	3 (barrier soil liner)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	5.8		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.062	0.0574	0.0526	0.0574
4	1	12		0.372	0.204	0.109	0.204
5	2	12		0.378	0.116	0.040	0.116
6	4	0.2					
7	1	58.57		0.37	0.24	0.136	0.24
8	2	24		0.374	0.0851	0.0203	0.0851
9	3	8		0.19	0.18	0.17	0.19
10	1	240		0.42	0.41	0.40	0.41
11	3	24		0.19	0.18	0.17	0.19

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	4.01E-04					
4	1	4.60E-04					
5	2	2.10E-02	77	3			
6	4	5.00E-09					
7	1	1.00E-04					
8	2	9.61E-02	77	3			
9	3	3.16E-11					
10	1	1.00E-10					
11	3	3.16E-11					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	4	0	59,458	1	
7	1				
8	2				
9	3				
10	1				
11	3				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-6, Infiltration through Degraded Closure Cap without Vault 2 (1,000 Years) HELP Model Input Data File: V2C1K.D10; and Output File: V2C1Kout.OUT (input file based upon previous file ZMSED4.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.01 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	450 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 54.4	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	4 (flexible membrane liner)
Lower Backfill	7	1 (vertical percolation layer)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	5.8		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.062	0.0574	0.0526	0.0574
4	1	12		0.372	0.204	0.109	0.204
5	2	12		0.378	0.116	0.040	0.116
6	4	0.2					
7	1	58.57		0.37	0.24	0.136	0.24

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	4.01E-04					
4	1	4.60E-04					
5	2	2.10E-02	450	3			
6	4	5.00E-09					
7	1	1.00E-04					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	4	0	59,458	1	
7	1				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

* The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-7, Infiltration through Degraded Closure Cap and Vault 2 with HDPE Geomembrane (10,000 Years)
HELP Model Input Data File: V2F10K.D10; and Output File: V2F10Kou.OUT (input file based upon previous file ZMSED8.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.002 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	**CN Input Parameter Value**
Slope =	3 %
Slope length =	77 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 60.0	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	4 (flexible membrane liner)
Lower Backfill	7	1 (vertical percolation layer)
Lower Drainage Layer	8	2 (lateral drainage layer)
Roof HDPE	9	4 (flexible membrane liner)
Concrete Vault Roof	10	3 (barrier soil liner)
Saltstone	11	1 (vertical percolation layer)
Floor HDPE	12	4 (flexible membrane liner)
Concrete Vault Floor	13	3 (barrier soil liner)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	4		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.088	0.0726	0.0596	0.0726
4	1	12		0.375	0.16	0.0745	0.16
5	2	12		0.375	0.16	0.0745	0.16
6	4	0.2					
7	1	58.57		0.37	0.24	0.136	0.24
8	2	24		0.248	0.188	0.168	0.188
9	4	0.1					
10	3	8		0.19	0.18	0.17	0.19
11	1	240		0.42	0.41	0.40	0.41
12	4	0.1					
13	3	24		0.19	0.18	0.17	0.19

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	4.51E-04					
4	1	3.20E-03					
5	2	3.20E-03	77	3			
6	4	5.00E-09					
7	1	1.00E-04					
8	2	1.74E-02	77	3			
9	4	2.00E-13					
10	3	1.00E-09					
11	1	1.00E-09					
12	4	2.00E-13					
13	3	1.00E-09					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	4	0	728,360	1	
7	1				
8	2				
9	4	0	35,208	3	
10	3				
11	1				
12	4	0	35,208	3	
13	3				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

* The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-8, Infiltration through Degraded Closure Cap and Vault 2 without HDPE Geomembrane (10,000 Years)
HELP Model Input Data File: V210K.D10; and Output File: V210Kout.OUT (input file based upon previous file ZMSED8.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.002 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches

CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	77 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 60.0	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	4 (flexible membrane liner)
Lower Backfill	7	1 (vertical percolation layer)
Lower Drainage Layer	8	2 (lateral drainage layer)
Concrete Vault Roof	9	3 (barrier soil liner)
Saltstone	10	1 (vertical percolation layer)
Concrete Vault Floor	11	3 (barrier soil liner)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	4		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.088	0.0726	0.0596	0.0726
4	1	12		0.375	0.16	0.0745	0.16
5	2	12		0.375	0.16	0.0745	0.16
6	4	0.2					
7	1	58.57		0.37	0.24	0.136	0.24
8	2	24		0.248	0.188	0.168	0.188
9	3	8		0.19	0.18	0.17	0.19
10	1	240		0.42	0.41	0.40	0.41
11	3	24		0.19	0.18	0.17	0.19

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	4.51E-04					
4	1	3.20E-03					
5	2	3.20E-03	77	3			
6	4	5.00E-09					
7	1	1.00E-04					
8	2	1.74E-02	77	3			
9	3	1.00E-09					
10	1	1.00E-09					
11	4	1.00E-09					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	4	0	728,360	1	
7	1				
8	2				
9	3				
10	1				
11	3				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

Table D-9, Infiltration through Degraded Closure Cap without Vault 2 (10,000 Years) HELP Model Input Data File: V2C10K.D10; and Output File: V2C10Kou.OUT (input file based upon previous file ZMSED8.D10 from Phifer 2003)

Input Data:

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.01 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	450 ft
Soil Texture =	5 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 54.4	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Upper Drainage Layer	5	2 (lateral drainage layer)
Upper GCL	6	4 (flexible membrane liner)
Lower Backfill	7	1 (vertical percolation layer)

	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture (Vol/Vol)
1	1	4		0.4	0.11	0.058	0.11
2	1	30		0.37	0.24	0.136	0.24
3	1	12		0.088	0.0726	0.0596	0.0726
4	1	12		0.375	0.16	0.0745	0.16
5	2	12		0.375	0.16	0.0745	0.16
6	4	0.2					
7	1	58.57		0.37	0.24	0.136	0.24

Input Data (continued):

	Layer Type	Sat. Hyd. Conductivity * (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	1.00E-03					
2	1	1.00E-04					
3	1	4.51E-04					
4	1	3.20E-03					
5	2	3.20E-03	450	3			
6	4	5.00E-09					
7	1	1.00E-04					

	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
1	1				
2	1				
3	1				
4	1				
5	2				
6	4	0	728,360	1	
7	1				

The lack of values in the table for particular parameters in particular layers denotes that no HELP model input was required for that parameter in that layer. No data are missing from the table.

* The HELP model output often produces an increased number of significant digits for the Effective Saturated Hydraulic Conductivity over that of the actual input.

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